Techniques development for the reestablishment of the long-spined sea urchin, *Diadema antillarum*, on two small patch reefs in the upper Florida Keys

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Abstract

A project funded through FKNMS was begun in the fall of 2001 offshore of the Upper Keys to explore the feasibility and ecological results of translocating juvenile long-spined sea urchins, *Diadema antillarum*, from areas with relatively high settlement and extensive winter mortality, the reef crest rubble zones, to nearby deeper water (about 25 feet, 7.5 m) patch reefs at densities approaching those on Florida reefs before the *Diadema* plague of the early 1980s. Four patch reefs: two experimental and two controls, varying in size from about 44 to 96 sq. m were selected for the study. During the period from September 2001 to December 2001, 434 juvenile long-spined urchins were placed on experimental reef # 1 (96 sq. m), a total potential density of 4.5/m^2, and 262 were placed on experimental reef # 2 (88 sq. m), a potential density of 3.0/m^2. An additional 16 urchins were placed on reef # 2 on 10/23/02 bringing the total urchins placed on reef # 2 to 278, a potential density of 3.2/m^2. The translocated populations were evaluated for number and placement of surviving urchins 10 times on reef # 1, and 11 times on reef # 2 over various intervals during the period from September 8, 2001 to February 5, 2003.

Percent survival of the *Diadema* urchins was roughly similar on both experimental reefs from the first count on 09/08/01 through the final count on 02/05/03. Initial survival rates over the first three days of 80% and 90% dropped to about 40% to 45% on both reefs from 11/09/01 to 05/29/02, and then, on experimental reef # 1, survival remained at about 30% from 08/08/02 to the last count on 02/05/03. On experimental reef # 2, survival remained at 40% on 08/08/02, dropped to 30% on 10/08/02 and then dropped again to 17% at the count on 11/30/02. Survival was 20% on the final count on 02/05/03 due to placement of 16 urchins on this reef late in the study (10/23/02). The average density of urchins over the entire 17 months of the study was 1.6m/^{2} on experimental reef # 1 and 1.0/m^2 on reef # 2. The highest density on reef # 1 (2.1/m^2) was achieved on 02/26/02 and the highest density on reef # 2 (1.4/m^2) occurred on 10/24/01 and on 02/26/02. The final density on 02/05/03 on reef # 1 was 1.2/m^2 and on reef # 2 was 0.6/m^2. Decline in survival and density on both reefs was generally gradual and stable at a similar rate of decline during the last 12 months of the study. Reef # 1 lost 87 urchins, a survival of 57% over the last 345 days of the study. The total loss in urchin density on reef # 1 over this period, 02/26/02 to 02/05/03, was 0.9/m^2, which was a decline in density of 0.0026/m^2 per day. Reef # 2 lost 67 urchins during this 345-day period, a survival of 45% and a loss in density of 0.8/m^2; which was a decline in density of 0.0023/m^2 per day (This data for reef # 2 includes 16 urchins released on reef # 2 on 10/23/02).

The gradual mortality over the term of the project indicated that predation was the main cause of population decline and not mortality due to storms or plague. Population counts before and after two instances of tropical storm conditions in the fall of 2001 indicated that these storms did not cause mortality in the translocated urchin populations on the experimental deep reefs, and no evidence of plague caused *Diadema* urchin death was observed.

Although evidence of some movement between reef quadrants and some concentration of urchins on the more rugged and complex areas of reef # 1 was evident, in general, urchins remained broadly distributed over all reef areas on each experimental reef.

NURC (NOAA's National Undersea Research Center) conducted a rapid habitat assessment of the four project reefs on 08/31/01 and 09/01/01, before translocation of the urchins and again on 09/18/02, about one year after translocation of the urchins.
The benthic ecology of the experimental reefs changed considerably during the period of exposure to "normal" pre plague density of *Diadema* urchins. The results of the NURC assessment showed that the percent stony coral cover increased on the experimental reefs from 9.8% to 15.3% (+ 56% relative increase) and decreased on the control reefs from 9.1% to 6.8% (-26% relative decrease). Sponge cover decreased on the experimental reefs from a mean of 7.4% to 5.3% and increased on the control reefs from 5.3% to 6.0%. Algal turf cover decreased slightly on the experimental reefs from 28% to 24% (- 16.2% relative decrease) while algal turf increased on the control reefs from 23.4% to 27.8% (+18.7% relative increase). Crustose coralline algae exhibited the most significant change. Coralline algae cover increased on the experimental reefs from 7.5% to 19% (+ 153% relative increase) while coralline algae cover decreased on control site 1 (reef # 3) and slightly increased on control site 2 (reef # 4), a total change of 7.8% to 8.8% (+ 6.5% relative increase) on the control sites. The presence of crustose coralline algae has been shown to stimulate settlement of certain species of stony corals. Green calcareous algae (mostly *Halimeda* spp.) showed little change on the experimental reefs (a decline from 3.8% to 3.1%), but increased on the control sites (an increase of 1.8% to 3.8%). Brown foliose algae, mostly *Dictyota* spp., greatly declined on the experimental reefs a decrease of 10% to 5.1%, a – 48% relative decrease) and increased slightly on the control reefs (an increase of 4.5% to 5.9% increase, + 31% relative increase). Brown foliose algae declined on experimental reef # 1 to a remarkable extent (11% to 1.8%, a – 511.1% decrease), and also declined on control reef # 4 (which hosted a small population of *Diadema* urchins) from 3.0% down to 1.0%. Experimental reef # 2 showed a small decrease in brown foliose algae from 9.0 to 8.5%, while control site 1 (reef # 3) showed an increase in brown foliose algae from 6.0% to 10.8%. Brown foliose algae are important competitors with corals for space and sunlight, and reduction of these algae is critical to coral recovery. The density of juvenile corals increased on the experimental reefs from an average of 6.2 juveniles/m^2 to 15.3 juveniles/m^2, a relative increase of + 147%. Average (mean) densities also increased on the control sites (reefs # 3 and # 4) but to a lesser degree, 6.6 juveniles/m^2 to 9.9 juveniles/m^2, a relative increase of +51%.

These positive changes over the short term of one year show a marked reduction in algal prevalence and signify a return to a coral dominated ecology. These changes in the ecology of the experimental reefs are what was expected from a return of *Diadema* urchins to the reefs, and reflect the changes that have occurred on limited areas of Caribbean reefs where populations of *Diadema* have returned naturally. This study presents evidence that translocation of *Diadema* urchins from environments with high risk of mortality to deeper reef areas along the Florida Keys results in survival and population densities that can affect change in the ecology of coral reefs, moving reefs areas from algal expansion back toward dominance of coral growth.

Introduction

The first 14 months and the final funding period of this project is now complete. This year-end report includes an account of the work accomplished and presentation and analysis of the data collected during the project. NOAA's National Undersea Research Center (NURC) has completed the benthic community assessment conducted before *Diadema* urchin translocation (September 1, 2001) and the assessment conducted one year after translocation (September 18, 2002). The year-end NURC report contains extensive information on the recent history of *Diadema* populations and benthic ecology in the Caribbean and Florida Keys as well as an analysis of changes in the benthic communities of the four project reefs. This report is included in this document as Appendix 1. The original project proposal (May 4, 2001), the first interim report (September 17, 2001), and the second interim report (March 2, 2002) are included as Appendices 2, 3, and 4. The first NURC report is included in Appendix 2, the first interim project report. Appendix 5 contains speculations on the possibilities and potential beneficial effects of stimulating and/or augmenting the return of *Diadema* populations to the Florida Keys reefs. This year-end report will briefly summarize the conduct of the project and include analysis of the translocated *Diadema* populations on the experimental reefs over the first year. The information contained in the appendices will be briefly summarized where necessary, with reference to the pertinent document.

The coral reefs that compose the Florida Keys barrier reefs have been in decline for several decades. The reasons for this decline are many and varied, some are well documented and some are still only speculation. However, one factor strongly contributing to the decline of Caribbean, Bahamian, and Florida coral reefs has been attributed to the almost total loss, 97 to 99 percent, of the long spined sea urchin, *Diadema antillarum*, in an unprecedented disease pandemic on a single marine organism that occurred in 1983-84. The *Diadema* sea urchin was the keystone herbivore in this region and the loss of this animal shifted the balance on the reefs from coral dominance to uncontrolled macro algae growth. Despite the passage of 20 years and the sporadic and variable presence of small pockets of *Diadema* in the Florida reef environment, this keystone herbivore has not repopulated the reefs and macro algae continues to dominate most of coral reefs in this ecosystem. Please see Appendix 1 and 2 for a complete history and documentation of the *Diadema* plague and its apparent effect on the coral reefs of this region.

In the fall of 2000, Ken Nedimyer and Martin Moe began work on a project to establish a pre-plague population level of *Diadama* sea urchins on two small patch reefs in the

Upper Keys. The purpose of this project was to explore the survival of translocated urchins in this environment and the effects that this urchin population may have on the benthic ecology of these reefs. The Florida Keys National Marine Sanctuary (FKNMS) provided the funding and along with the NOAA National Undersea Research Center (NURC) aided in the design of the project. The rationale for the project was to collect juvenile *Diadema antillarum* from shallow rubble areas on the reef crest where they settle in the late summer and fall of each year, but apparently do not survive the fall and winter storms that churn this area, and translocate them to deeper patch reefs before they disappear from the shallow rubble zones. Two experimental and two control reefs were to be selected for this work.

As stated in the project proposal (Appendix 2) the goals of this project were as follows.

"The overarching goal of this project is to monitor and track the success of one technique to enhance and restore coral reef areas. Specifically, the transplantation of large numbers of small *Diadema antillarum* from shallow rubble zones to deeper patch reefs will be evaluated. Additionally, the resulting effects of increased densities of *Diadema antillarum* to approximate pre-plague levels on small, isolated patch reefs will be monitored to determine if a reduction of algal overgrowth will enhance coral growth and settlement."

As stated in the project proposal (Appendix 2), there were four specific biological objectives in this project.

"1. Determine if *Diadema* urchins survive transplantation and the size that exhibits the best survival rate after transplantation.

2. Estimate the survival rates and the growth rates of transplanted *Diadema*.

3. Determine the distribution patterns that *Diadema* urchins develop on the test reef. (They will be placed initially in protected microhabitats within the reef structure and this initial distribution will be recorded on maps of the patch reefs.)

4. Compare and contrast general reef condition and community level changes, including coral recruitment and growth, on the manipulated and reference reefs over time."

Methods and Materials

The patch reefs about four miles eastward offshore of Tavernier, FL were explored and examined during the spring and summer of 2001 and four small patch reefs were selected for this project. Two of these reefs were designated as the experimental reefs (reefs 1 and 2) and two as the reference (control) reefs (reefs 3 and 4). The two experimental reefs are superficially different; reef #1 (about 96 sq. m) is relatively rugged and contains some large coral formations mostly at the southern end while reef #2 (about 88 sq. m) exhibits lower relief without the large *Montastraea cavernosa* bolder corals that occupy reef # 1. The two control reefs are located in the same vicinity as the experimental reefs. Control reef # 3 (about 72 sq. m) is generally similar to experimental reef # 2, while control reef # 4 (about 44 sq. m) is generally similar to experimental reef # 1. The maximum relief reported by the NURC surveys (Table 1, Appendix 1) was about 80 cm for experimental reef # 1, compared to 62 cm for control reef # 4, and about 43 cm for experimental reef # 2 compared to about 43 cm for control reef # 3. Appendix # 1, the year-end report from NURC contains a detailed biological description of all four project reefs and Appendix 3, the first interim project report contains location data (GPS numbers) and grid maps depicting the size and placement of the major coral formations on each reef.

Each of the four project reefs was carefully mapped and photographed before translocation of the *Diadema* urchins was begun. A sub-surface buoy was placed on each reef to mark the location without an attention generating surface marker. A north – south and an east – west transect line was established at about the center of each reef, dividing each reef into four quadrants. Each of these quadrants, NW, NE, SW, and SE, were then marked off into 4 square meter divisions to facilitate accurate recording of placement and subsequent location of the urchins during counts. Each experimental reef fit into a rectangle composed of 30, 4 sq. m sectors laid out six sectors on the north – south axis and 5 sectors on the east – west axis. On reef # 1 the north – south axis was extended along the line dividing three 4 sq. m sectors to the west and two 4 sq. m sectors to the east. On reef # 2 the north – south axis divided the reef two sectors to the west and three sectors to the east. The east – west axis on both reef # 1 and # 2 divided the reef in the center, three sectors to the north and three sectors to the south. A square pvc pipe frame two meters on each side was used to measure and temporarily demark each 4 sq. m sector and served as a frame for photographs. A map of the location and approximate size of the coral formations that compose each reef was recorded *in situ* with pencil on a plastic slate on which the 4 sq. m sectors, 120 sq. m total area, were laid out with a permanent marker. Later the representations of the coral formations were traced with a permanent marker and permanent map of each reef was drawn on the plastic slate.

These reefs are not exactly rectangular in shape however; there are areas of dense hard and soft coral structure exhibiting rugged relief, areas of low relief with scattered coral formations, and some areas with only seagrass and sand bottom within the delimited grid pattern of the reef. For the purpose of determining the density of *Diadema* urchins on each reef and on each quadrant of each reef, those 4 sq. m sectors that contained little or no reef structure on the periphery of the reefs were eliminated from the calculations of reef area.

Six of these sectors were omitted from reef # 1, resulting in a total reef area of 96 sq. m. One square sector was omitted from the NW quadrant resulting in a reef area of 32 sq. m; one sector was omitted from the NE quadrant resulting in a reef area of 20 sq. m; three square sectors were omitted from the SW quadrant resulting in a reef area of 24 sq. m; and one sector was omitted from the SE quadrant resulting in a reef area of 20 sq. m.

For reef # 2, which was smaller in extent and structure than reef #1, a total of eight 4 sq. m sectors were omitted, resulting in a total reef area of 88 sq. m. One square sector was omitted from the NW quadrant resulting in a reef area of 20 sq. m; three sectors were omitted from the NE quadrant resulting in a reef area of 24 sq. m; one square sector was omitted from the SW quadrant resulting in a reef area of 24 sq. m; and three sectors were omitted from the SE quadrant resulting in a reef area of 20 sq. m. Figure one illustrates the working map of each experimental reef, including demarcation of those 4 sq. m sectors omitted from reef area determinations.

Juvenile *Diadema* urchins were collected on the shallow rubble zones at the reef crest at Conch and Pickles reefs during 10 trips to one or both sites from September to December 2001. Collection and effort data are contained in Table 1. The urchins were collected by carefully removing them from under or between the rubble rocks with a short aluminum rod and flipping them into a large, small mesh hand net. When the net was full, they were returned to the boat and placed in holding tanks. The collected urchins were sorted by size; small, test size about 1 to 2.5 cm; medium, test size about 2.6 to 4.0 cm; and large, test size about 4.5 to 6 cm. Usually, two collectors worked the rubble bottoms and one additional person in the boat helped to transfer the urchins to the holding tanks. The effort reported in Table 1 consists only of the total collector hours expended during each collection trip, variously consisting of one, two, or three collectors. A total of 30 collection hours were expended to take 741 urchins. There was an average yield of 25 urchins per collector hour.

Immediately after collection, the urchins were transported by boat to the experimental reefs. Divers carried the urchins down to the reefs, where they were liberated next to coral formations. Upon being released from the net, the urchins immediately moved toward and into the nearby coral structures. No urchin seemed to be exposed without shelter for more than a few minutes. No predation on newly released urchins was observed. The specific location of release of each urchin was recorded on a plastic slate on a map of the reef drawn on the slate.

Counts of the urchins on the experimental reefs were made at various intervals beginning a few days after the release of the first translocated urchins on September 8, 2001 and extending to the last count on February 05, 2003. Table 2 contains the data on the dates and numbers of urchins released on each experimental reef, the results of all the counts, and the percent survival on each reef at the time of each count. Counts of surviving urchins on each experimental reef were made as weather and opportunity allowed. On those occasions when a count (population evaluation) was made on the same day as a collection of juvenile urchins, the count of the surviving *Diadema* population on the reefs was made before release of the collected juvenile urchins. An exception to this occurred on the October 24, 2001 count on reef #2. In this instance, to prevent inflation of the survival data on that count, the number of urchins released was subtracted from the number counted on that date. Also, 16 urchins released on reef # 2 on October 23, 2002 were subtracted from the count on November 30, 2002 to provide more accurate survival data on that count.

A total of 11 counts (10 on reef # 1 and 11 on reef # 2) were made over the course of the project. Ken Nedimyer made all the counts of surviving urchins. Ken carefully surveyed each quadrant of the experimental reefs and recorded in pencil on the reef map slate the presence and location of every urchin he observed. A paper copy of the reef map with the date and count notations was made later and then the penciled notations were erased and the slate reused on the next count.

An extensive series of photographs was made of each experimental reef before placement of the urchins on the reef and then at various times after placement of the urchins. The reefs were not disturbed by collection of organisms or relocation of any urchins after initial placement. Two exceptions to this were the removal of two large spotted burrfish, *Chilomycterus atinga*, the first on September 3, 2001, the day before initial placement of urchins on the reef, and the second during a night dive on August 28, 2002. The first burrfish was removed from the NE quadrant of reef # 1 where there was evidence at that time (crushed coral and broken shells) that the burrfish frequently occupied a specific sheltered area under a coral formation. The second was also taken on reef # 1 as it moved about this area during the night. It also apparently frequented the same sheltered coral cave area on the NE quadrant as the first burrfish, as crushed shells and urchin spines were present. Remains of freshly crushed urchins on reef # 2 indicated that the burrfish also frequented nearby reef #2. The second burrfish was taken immediately after feeding on urchins since bits of *Diadema* test and spines were present in the area where it was taken and also found later on the bottom of the holding tank where it was placed after capture.

Documentation of the condition of the benthic ecology of the experimental reefs and the reference reefs was conducted by NOAA's National Undersea Research Center (NURC) on August 31 to September 1, 2001 before placement of the urchins on the experimental reefs and again on September 18, 2001, about one year after placement of *Diadema* urchins on the experimental reefs. Appendix 1 is the paper prepared by NURC that details the changes that occurred on both the experimental reefs with the translocated *Diadema* populations and the reference reefs during the first year of this project.

Results

The results of this project fall into two basic categories: The progressive survival and status of the *Diadema* populations on the experimental reefs, and the analysis and documentation of the condition and changes in the benthic ecology of the experimental and control reefs over the term of the project.

***Diadema* populations on the experimental reefs**

Collection of juvenile *Diadema* from the shallow rubble zones during good weather and sea conditions was not physically or technically difficult. The juveniles are variously abundant in these areas during late summer, fall, and early winter depending on settlement success and occurrence and intensity of storms during this period. Table 1 presents the collection data and effort in collector hours for the juvenile *Diadema* collected during the first four months of the project. Small *Diadema*, test size under about 2.5 cm in diameter, are very secretive and can be difficult to find. Although the average of the effort data shows that 25 urchins per hour were taken during these collection trips, an experienced collector, depending on conditions, would be considerably more productive than a novice collector. Also, the numbers of juvenile urchins in these shallow rubble zones varies considerably depending on strength of recruitment, occurrence of storms, depth, and time of the year. Thus when juvenile urchins are abundant, large numbers can be quickly collected and when they are scarce, collection is more difficult.

We intended to attain a concentration of about 4 *Diadema* per square meter on each experimental reef to approximate the reported, near maximum pre plague densities of *Diadema* on Florida Keys reefs of 4 to 5/m^2. With limited collection effort, juvenile *Diadema* were available on the rubble zones of Conch and Pickles reefs during the early fall of 2001 in just enough abundance to provide the desired pre plague *Diadema* urchin density (about 3 to 4.5/m^2) on each reef. Despite high mortality in the first few months, a sustained average density of 1 to 2 urchins (1.7/m^2 on reef # 1 and 1.1/m^2 on reef # 2) was maintained over the course of the project.

Table 2 presents the data on the total numbers of *Diadema* released on experimental reefs 1 and 2, the numbers counted at each population evaluation on each reef, and the percent apparent survival rate of the urchins on each reef at the time of each count. The survival rate is termed "apparent survival" because it is quite possible, especially when early juveniles were abundant, that some urchins were deeply hidden in the reef structure and were not observed. Thus the survival rate may possibly have been slightly higher, but not lower than that recorded. Figure 2 graphically illustrates the cumulative number of urchins released on experimental reef # 1 before the count and the number counted on this reef on the date of each count. Figure 3 graphically illustrates the cumulative number of urchins released on experimental reef # 2 before the count and the number counted on this reef on the date of each count. Figure 4 graphically illustrates the combined release and count data for both experimental reefs, and Figure 5 graphically depicts and compares the percent apparent survival based on density (#/m^2 counted/#/m^2 released) for both experimental reefs on the date of each population evaluation (count). Figure 6 illustrates the changes in density, numbers of *Diadema* urchins per sq. m (#/m^2) on each experimental reef at each count.

Survival, distribution, and movement of *Diadema* on the experimental reefs.

Survival rates were high during the first weeks after initial translocation of urchins to the experimental reefs. The initial translocation of juvenile *Diadema* occurred on 09/04/01 and 09/05/01. A total of 201 (plus 11 on 09/17) were placed on reef #1 and 85 were placed on reef # 2. Percent apparent survival on reef # 1 by density (#/m^2 counted / #/m^2 released) over the first 14 days (09/05 to 09/19) was 82% on reef # 1 and 90% on reef #2.

Storm mortality

The Upper Florida Keys were brushed by two fall storms early in the project, strong Tropical Storm Gabrielle on September 14, 2001, and Hurricane Michelle on November 5, 2001. The Upper Keys area experienced sustained winds of about 25 to 30 knots and gusts of about 40 knots in both storms. There was evidence of the effects of storm surges (sedimentation, movement of some corals and rocks, accumulations of loose seagrass and seaweed) on the experimental reefs after both storms.

Tropical Storm Gabrielle passed westward over the center of the Florida peninsular, well north of the Keys, which experienced the very fringes of the southern side of the storm, with winds mostly southerly. Loss of *Diadema* on the experimental reefs due to Gabrielle was minimal or none as the percent apparent survival (#/m^2 counted / #/m^2 released) on reef # 1 and reef # 2 on 09/08 were, respectively, 81% (1.7/m^2) and 90% (0.9/m^2) and the first counts after the storm 5 days later on 09/19, were 82% (1.8/m^2) and 90% (0.9/m^2) showing no loss in density. There was a release of 11 urchins on the NW quadrant of reef # 1 on 09/17 after the storm, and this is reflected in the increase in density on the NW quadrant in the 09/19 count from 1.8/m^2 (82% survival) to 2.2/m^2 (88% survival) an actual increase of 15 urchins on this quadrant. There was no loss in apparent survival or density of urchins on either reef before and after the storm so apparently there was no mortality due to passage of this storm. This indicates that the urchins on the deeper patch reefs can survive a significant storm event with no apparent mortality.

Hurricane Michelle passed westward through the Florida Straits on 11/05/01 about 100 miles SE of the Upper Florida Keys. The Florida Keys were on the northern side of the storm and experienced strong north easterly winds gusting to 50 knots (Molasses Reef) and storm surges of 1 to 3 feet (storm data from the NOAA Tropical Weather web site). The impact of Michelle to the Upper Keys appeared to be greater than the impact of Gabrielle.

Diadema survival on reef # 1 dropped from 82% on 09/19 to 45% on 11/09, 51 days later (4 days after Hurricane Michelle). During this 51 days, however, 155 additional urchins were translocated to reef # 1 (between 09/26 and 10/24), so although the percent survival (calculated as the #/m^2 counted / #/m^2 released) dropped by 37% over this period, the overall density of urchins on the reef dropped by only 0.1/m^2 (1.8/m^2 to 1.7/m^2). Thus even though percent survival dropped by about 37% over this 51 days, the density of urchins on reef # 1 was about the same at the time of both counts, before and after the storm. The rate of decline in apparent survival on reef # 1 over this 51-day period (09/19 to 11/09) was 0.7% per day.

The situation during this period on reef # 2 was more complex, and more revealing. A count of the urchins made on reef # 2 on 10/24, (reef #1 was not counted) 12 days before Hurricane Michelle, showed 61% survival of *Diadema*. This was a drop of 29% apparent survival over a period of 35 days (09/19 to 10/24), but a gain in density of 0.5m^2 from the previous count of 0.9/m^2 on 09/19 to 1.4/m^2 on 10/24. The gain in density was a result of the placement of 132 translocated *Diadema* on reef # 2 on 09/19 and 09/21. The rate of decline of urchins on reef # 2 during the 35 days before the storm was 0.8% per day.

The count on 11/09 (1.3/m^2), 4 days after the hurricane, showed 48% survival on reef # 2, a drop of 13% from the 61% survival of the previous count (0.1/m^2) on 10/24, 16 days prior. However, the rate of decline, 0.8% per day, was the same for the 35-day period before (09/19 to 10/24) and the 16-day period that included the storm (10/24 to 11/09). This indicates that on reef # 2, Michelle did not cause mortality great enough to increase the daily rate of mortality in the 16 days that included the storm over that that occurred in the 35 days before the storm. The last translocation of urchins occurred 12 days before Hurricane Michelle on 10/24, with 21 placed on reef # 2, and 34 placed on reef # 1.

The placement of urchins on both reefs before Michelle (09/19 through 10/24) was almost equal, 155 on reef # 1 and 153 on reef # 2, and the time of release was also similar. The daily rate of mortality on reef # 1 (0.7% per day) over the 51 day period between 09/19 and 11/09, which included Hurricane Michelle, was very close to the daily rate of mortality (0.8% per day) that was experienced on reef # 2 during the period before (09/19 to 10/24) and the period including the storm (10/24 to 11/09). Also the overall survival rate on 11/09 was almost the same on both reefs, 45% on reef # 1 and 48 % on reef # 2.

Storm mortality analysis

Time line for counts and storms, 09/08/02 through 11/09/02
G – Gabrielle, M – Michaelle, C - count date

09/14 G **11/05 M**
09/08 C ! 09/19 C 10/24 C ! 11/09 C
____!__________!_________!____________________ !_______!_______!______

Survival percentage (#$m/^2$ counted / #$m/^2$ released x 100) and density (#$m/^2$)
! ! ! ! ! !
! ! ! ! ! !
(1) 81% 1.7$m/^2$! 82% 1.8$m/^2$! 45% 1.7$m/^2$
(2) 90% 0.9$m/^2$! 90% 0.9$m/^2$ 61% 1.7$m/^2$! 48% 1.3$m/^2$
! ! ! ! ! !
Daily percent rate of loss (#$m/^2$ counted / #$m/^2$ released x 100) / days elapsed
! ! ! ! ! !
(1) ! ----------no loss ----------!--------0.7% per day------------------------------!
(11 days) ! (51 days) ! ! !
(2) ! ----------no loss-----------!--------0.8% per day--------!--0.8% per day----!
! (11 days) ! (35 days) ! (16 days) !
! ! ! ! ! !
Urchins added to reefs
! ! ! ! ! !
(1) 201 11 79 42 34 (total 367) !
(2) 85 27 105 21 (total 238) !

The data above (approximate placement of dates) lays out the time line for counts, percent loss between counts, rate of daily loss from 09/19 to 10/24 to 11/09 (no loss from 09/08 to 09/19), and urchins added to the reefs during the period 09/08 to 11/09.

In summary, the absence of mortality on both reefs from 09/08 to 09/19, which included Tropical Storm Gabrielle; the same daily percent rate of loss on reef # 2 (0.8%) during the 35 day period before (09/19 to 10/24) and the 16 day period (10/24 to 11/09) that included Michelle on reef # 2 (0.8%); the close similarity of the daily percent rate of loss on reef #1 and # 2 on during the 51 days between 09/19 and 11/09, which included Michelle; and the parallel survival rates (45% and 48%) on both reefs on 11/09; indicate that mortality patterns on both reefs were very similar during the 51 days from 09/19 to 11/30 and that there was no precipitous mortality of urchins on either reef immediately after either storm. The data suggest a gradual loss of urchins over time rather than a rapid loss immediately after Michelle on reef # 2 and the pattern of loss on both reefs is so similar that if this storm did not cause considerable mortality on reef # 2, then it probably didn't cause such mortality on reef # 1 either. This analysis shows that no urchin mortality was caused by Tropical Storm Gabrielle, and indicates, but does not conclusively prove, that precipitous mortality of *Diadema* did not occur as a result of the proximity of Hurricane Michelle.

Although these strong storms apparently did not greatly affect *Diadema* populations on these deep (about 25 feet, 7.5 m) patch reefs, the shallow rubble zones on the reef crest absorb much more storm energy and the wave surge rolls and grinds the rubble rock and destroys the small urchins that have settled on the scoured rock surfaces. Thus the same wave energy that seems to prepare the rock surface for settlement of the post larval *Diadema* urchins also destroys the juveniles that grow and develop in this environment over the late summer and fall months. Ken Nedimyer recently (01/03/03) visited the rubble zone at the north end of Conch reef after winter storms and observed a few, about 10, healthy *Diadema* urchins in the deeper areas, about 8 to 10 feet (3 m) along with 3 dead urchins and about 7 with their spines missing. There were no urchins present in the shallow areas, 3 to 4 feet (1.2 m). A strong sea surge was breaking over the south end of Conch reef at the time of his visit.

The initial loss over the first three days, about 19% on reef # 1 and 10% on reef #2, occurred before the storms and was most likely a loss of small juveniles, presumably to predation. Small juveniles, however, can hide far under and deeply into coral and rock structures and it is possible that we could not observe all that were present and that the losses after the first three days were not as great as the count indicates. The much greater loss (81% survival) on the more rugged reef # 1 compared to the smaller loss (90% survival) on the low relief of reef # 2 indicates that either predation was much greater on reef # 1 over these three days or that the small urchins were better hidden.

Losses of about 55% (45% survival) on reef # 1 and 52% (48% survival) on reef # 2 occurred during the first 65 days, and although both storms were included in this period, there was no loss of urchins from Gabrielle and apparently little, if any, direct loss from Michelle.

Survival rates seemed to remain constant at about 45 percent on both reefs during the fall and winter months. Mortality on reef # 1 was apparently a bit greater since 67 additional urchins were translocated to reef #1 on 12/20/01 with only 24 urchins translocated to reef

#2 on that same day. Thus reef #1 had 43 more urchins added to its population in December 2001 than reef #2. The placement of additional urchins on these reefs during the first four months of the study accounts for the preservation of the density of urchins on the reefs despite the numerical loss of urchins between counts.

Except for the placement of 16 large urchins, test size 3.5 to 6 cm, on reef # 2 on 10/23/02, the 12/20 translocations were the last placement of urchins on the experimental reefs for the duration of the study. The survival data from the last 345 days of the study, 02/26/02 to 02/05/03 were most important since few additions of urchins to the reefs affected the survival rates during this period. The 16 large urchins released on reef # 2 on 10/23/02 were subtracted from the count on 11/30/02 on reef # 2 to avoid inflation of the survival data on that count. We felt that it was quite likely that all of these 16 large urchins could have easily survived the 38 days between release and the count on 11/30, and to include them would skew the data to indicate a higher survival rate on reef # 2 at that count than that that had actually occurred.

Thus the total number released on reef # 2 was recorded as 262 rather than 278 for the 11/30/02 count and the number surviving at this count was recorded as 47 rather than the 63 actually counted. Therefore the density of on the 11/30/02 count for reef # 2 was $0.5/m^2$, and the percent survival ($\#/m^2$ counted / $\#/m^2$ released) at this count was 17%. The 16 urchins released on 10/23/02, however, were included in the final count made on 02/05/03 and this accounted for the increase in survival from 17% to 20%, density, $0.5/m^2$ to $0.6/m^2$, and percent mortality (as loss of density) from 83% to 80%, and the decrease in the percent loss or urchins per day from 0.18% to 0.15% between the 11/30/02 count and the final count on 02/05/03.

Elimination of these 16 urchins also changes the data for the 11/30/02 count of the urchins released on the NE and SE quadrants of reef # 2, eliminating 8 from this count on each of these quadrants. The release and count including these 16 urchins released on 10/23/02 is recorded in Table 2, but the corrected values reflecting the elimination of these 16 urchins from the data on this count are recorded in Tables 4, 6, and 7 and on the resulting graphs as well.

Survival rates on both reefs held constant at 45 to 47 percent over the winter months of December and January, and dropped to 42 and 40 percent by May 29, 2002, about 9 months after initial translocation. *Diadema* populations on the experimental reefs were not evaluated again until August 08, about 2 months later. Apparent survival dropped to 31% on reef #1 and 40% on reef #2 during this period. Two months later, October 08, apparent survival had dropped again to 29% on reef # 1 and 30% on reef # 2, and about two months later, November 30, apparent survival, about a year after translocation of almost all the urchins, was 27% on reef # 1 and only 17% on reef # 2 (excluding the 16 additional urchins that were added to reef # 2 on October 23, 2002). The last count on 02/05/03 showed a loss of only 4 urchins on reef #1, 119 down to 15, which registered as no loss in survival, 27%, based on density of urchins. Survival, based on density, increased on reef #2 from 17% to 20%, despite a numerical loss of 8 urchins, 63 down to 55, due to the placement of the 16 urchins on 10/23/02.

By December 2001, 434 juvenile urchins had been released on experimental reef #1 (reef area of about 96 sq. m), which without any mortality would have been a density of $4.5/m^2$. The highest *Diadema* density recorded on reef # 1 was $2.1/m^2$ and occurred on the February 26 population evaluation (count). After about 17 months, the urchin density on reef # 1 was $1.2/m^2$ (the lowest recorded density) with an apparent survival rate of 27%. The density of urchins per square meter on reef #1 at the first count on September 08, 2001, was $1.7/m^2$ and $1.2/m^2$ at the last count on February 5, 2003. The average density of *Diadema* urchins on reef #1 over the duration of the project was $1.6/m^2$

A total of 278 urchins (including the 16 released on 10/23/02) were released on reef # 2, (reef area of about 88 sq. m) which without any mortality would have been a density of $2.98/m^2$. The highest *Diadema* density recorded on reef # 2 was $1.4/m^2$ and occurred on the count made on October 24, 2001 and again on the count made on February 26, 2002 (45 urchins were released on reef # 2 between these counts). After 17 months the urchin density on reef #2 was $0.6/m^2$ with an apparent survival rate of 20%. The average density of *Diadema* urchins on reef #2 over the duration of the project was $1.0/m^2$.

The total area of reef structure of both experimental reefs was 184 sq. m. By number, 61%, 434, of the 712 urchins were placed on reef # 1 and 39 %, 278, were placed on reef # 2. Numerically, by 02/05/03 reef # 1 lost 74% of the urchins placed on the reef, and reef # 2 lost 80% of the urchins placed on that reef. The potential density of the release of 712 urchins combined for both reefs was $3.9/m^2$ and at the end of the study, the surviving density for both reefs combined was $0.9/m^2$. Despite considerable differences in numbers of urchins placed on each reef, a total potential density of $4.5/m^2$ on reef #1 and $3.2/m^2$ on reef # 2, the average (mean) density of *Diadema* urchins on both experimental reefs over the 17 month term of the project was $1.6/m^2$ on reef # 1 and $1.0/m^2$ on reef # 2, a difference of $0.6/m^2$. The total loss of density on reef # 1 ($4.5/m^2$ down to $1.2/m^2$) over the course of the study was $3.3/m^2$ compared to the loss of $2.6/m^2$ ($3.2/m^2$ down to $0.6/m^2$) on reef # 2 a greater loss of potential density of $0.7/m^2$ on reef # 1 than on reef # 2.

A difference of $0.6/m^2$ separated the total density of urchins on reef # 1 ($1.2/m^2$), from reef # 2 ($0.6/m^2$) 17 months after initial placement of urchins on these reefs. The overall urchin density was greater on reef # 1 than on reef # 2 at each count (Figure 6), but the percent apparent survival in density of urchins on each reef was very similar up the 08/08/02 count (Table 6, Figure 5). After excluding the 16 urchins added to reef # 2 on 10/23/02 for the 11/30/02 count, reef # 2 had a 58% decline in urchin density from $1.2/m^2$ down to $0.5/m^2$, between the 08/08/02 and the 11/30/02 counts. Reef # 1, however, with a density loss of $1.4/m^2$ down to $1.2/m^2$, a decline of only 14%, did not experience a similar loss over the same period. Predation seems the most likely cause for the precipitous decline on reef # 2, perhaps the relative scarcity of complex reef structure on reef # 2 made the urchins more available to predators on this reef.

Overall, however, the rate of loss of urchins on both reefs was similar. The daily rate of loss of percent density of urchins on both reefs was calculated by dividing the percent loss (mortality) of urchins (100 – (#/m^2 counted / #m^2 released x 100) on each experimental reef at the time of each count by the number days elapsed since the first translocation of urchins. This provided the daily rate of loss from the beginning of the project of the percent mortality at the time of each count (Table 7 and Figure 7).

The initial rapid loss of urchins is evidenced in the high daily rate of loss over the first 3 days after the first translocation. Although survival rates were relatively high over these 3 days, 81% on reef # 1 and 90% on reef # 2, the short time period of 3 days produced a high daily rate of loss, 6.3% per day on reef # 1 and 3.3% per day on reef # 2. It may be that the small juveniles that were translocated succumbed rapidly to predation or that many of these smallest urchins were not detected in the complex reef structures on the first count. Interestingly, despite the structural and area differences in the two reefs; the differences in the numbers of urchins released and counted on these reefs; and the varying number days between counts, after the initial period of 65 days; the daily rate of percent mortality on each reef is very close from Nov., 2001 to Feb. 2003 (Table 7). And this daily rate of loss was relatively stable on both reefs at about 0.2% from the May 29 count through the November 30 count. The average percent rate of loss per day from the total number of urchins that were placed on both reefs from the 02/26/02 count through the 11/30/02 count, 278 days, was 0.214 % on reef # 1 and 0.216% on reef #2, and the average loss of density from 02/26/02 to 11/30/02 was 0.9/m^2 on both reefs, a daily rate of density loss of 0.0032/m^2 per day on both reefs. In the 67-day period between the last two counts, 11/30/02 and 02/05/03, reef # 2 continued to loose urchin density (8 urchins, 0.09/m^2) more rapidly than reef # 1 (4 urchins, 0.04/m^2).

Predation due to mortality is assumed to the major cause of loss of urchins on the experimental reefs. However, it is possible that some urchins moved off the reefs onto other nearby reefs, a few large urchins were observed on control reef # 3 during a night dive on 08/28/02, but such movement would have had to occur over 40 to 50 feet (12 to 15 meters) of grass bed that separated experimental reef # 1 from control reef # 3, so we consider movement of urchins off the experimental reefs as possible, but unlikely.

Our primary interest in this project was to investigate the survival of the translocated *Diadema* urchins on the experimental reefs and the effect that these urchins may have on the benthic ecology of these reefs. Growth rates, movement of the urchins on the reefs, preference for particular micohabitats, and distribution of urchins on the reef were also of considerable interest, but the frequent monitoring and detailed experimental design required to fully explore these considerations were beyond the scope of this project. Analysis of the survival and/or movement of translocated *Diadema* urchins within each of the 4 sq. m sectors was not possible. However, analysis of the numbers of urchins released and the numbers counted in each quadrant of the experimental reefs at each population evaluation did yield interesting results.

Changes in the urchin populations on each quadrant of each reef would be due, in varying measure, to differential survival and/or movement of urchins between quadrants. The boundary line between quadrants often ran through coral reef structures so in some areas, urchins moving from one side of a coral head or complex coral structure to the other would move from one quadrant to another with relatively little actual linear movement. However, despite the inherent vagaries of urchin populations on the quadrants, some understanding of the distribution of the urchins on the reefs can be gleaned from this data.

Movement of an urchin from one quadrant to another registered as a loss to one quadrant and a gain to another. A gain in population would result from either movement into that quadrant or settlement of new recruits in that area. After the first two months, the presence of new recruits on any area of the experimental reefs would have been quite obvious, and newly settled *Diadema* would not have been noticeable on the reef during the first month. In a study of settlement of *Diadema* off Curacao, Bak (1985) reported growth of newly settled *Diadema* at about 3 to 6 mm in a two week period, and Forcucci (1994) estimated an early growth rate of about 7 mm per month for urchin on Florida Keys reefs. We would not have noticed newly settled *Diadema* until they had attained a test size of at least 5 mm, probably a month or so after settlement and such small urchins would have been quickly identified as recent recruits. Thus we are reasonably certain that few *Diadema* urchins settled and survived on these reefs until early fall of 2002.

Increases in populations on any quadrant are assumed due to movement to more "desirable" environments with better shelter and/or stronger algae growth. Decreases in populations may be due to urchin movement out of a particular quadrant or loss from predation (or other cause of mortality) within that quadrant. A study using spine tags to track individual urchins by Carpenter (1984) demonstrated that *Diadema* urchins returned with remarkable fidelity to the same daytime shelter and that the urchins avoided grazing on the same areas that were foraged the previous night.

Tables 3 and 4 list the cumulative numbers of *Diadema* urchins released on each quadrant of experimental reef #1 (Table 3) and experimental reef # 2 (Table 4) and the numbers of urchins observed in each of the quadrants on each reef at each count (population evaluation). Also listed in these tables are the density (#/m^2) of urchins released (cumulative) in each quadrant and the density (#/m^2) of urchins on the reef area of each quadrant at each count.

This data from each quadrant of each experimental reef is expressed as line graphs of the changes in density on each quadrant at each count. Figures 7 and 8 show the changes in density of urchin populations on each quadrant of reef # 1 and reef # 2. These line graphs compare the density of urchins cumulatively released on each quadrant with the density of urchins present on each quadrant at each population evaluation. Figures 9 and 10 show the changes in the percent density of urchin populations, (#/m^2 counted / #/m^2 released) on each quadrant of reef # 1 and reef # 2, and on the total reef area. These line graphs compare increase and/or decrease in density of urchin populations relative to the density of the total number of urchins released on each experimental reef and on each quadrant of each reef at the time of each population evaluation. They illustrate relative survival and/or accumulation of urchins in these areas.

Without marking individual urchins, it is not possible to know definitively whether a loss of urchins on a specific quadrant between counts was due primarily to movement to another quadrant or to mortality. However, an increase in the number of urchins on a specific quadrant in the absence of release of additional urchins on that quadrant must be due to movement of urchins into that quadrant. Also, an increase in urchin density in one quadrant over the same period as a decline in density in another quadrant may well be due to movement rather than differential mortality. A decline in density of urchins on a specific quadrant that was markedly less than declines on other quadrants and less than the reef wide decline as well, may be due to a movement of urchins into that quadrant, although significantly less mortality on that quadrant than on others cannot be discounted.

Reef # 1

The data on placement and count of urchins on each quadrant of reef # 1 over the course of the project is summarized in Table 3 and 5 and in Figures 8 and 10.There was evidence of some movement of *Diadema* on reef # 1 after initial placement. On reef # 1 the density of urchins on the SE quadrant increased from 1.7/m^2 to 2.2/m^2 (0.5/m^2, an increase from 68 to 92%) between the 09/08 and 09/19 counts without the addition of new urchins. The density of urchins on the SW quadrant declined by 0.4/ m^2 and the density on the NE quadrant declined by 0.3/m^2 without addition of new urchins, so it seems likely that urchins moved from the NE and SW quadrants into the SE (which has a border common to both NE and SW quadrants) over the 11 days between counts. The increase in density of 0.4/m^2 urchins in the NW quadrant was likely due to the placement of 11 urchins on this quadrant on 09/17.

The SE quadrant of reef # 1 contains large and complex bolder coral formations, *Montastraea cavernosa*, and covers a relatively small area, 20 sq. m. It would be expected that this large and complex reef structure would attract and contain a higher density of *Diadema* urchins because of the shelter that these structures offer. The SW quadrant of reef # 1 also contains large bolder coral structures and was a bit larger in total reef area, 24 sq. m, and the NE quadrant, same area as the SE quadrant, also contained some large coral structure. The NW quadrant, with less high and complex coral structure covered 24 sq. m.

Placement density of urchins in the quadrants of reef #1 (5.6/m^2 on SE, 5.5/m^2 on NE 4.4/m^2 on NW, and 3.0/m^2 on SW, Figure 7) varied considerably (Table 3, Figure 8). The two quadrants with the highest placement density, NE and SE, had the highest average density, NE 1.7/m^2 and SE at 2.1/m^2, over the course of the project. The quadrant with the lowest placement density, NW, had the lowest density, 0.6/m^2, only about half the density of the other three quadrants at the last count on 02/05/03. Evidently the urchins on the NW quadrant experienced a higher mortality rate or moved into the more rugged nearby quadrants. The percent apparent survival (47% and 36%) and the final density (1.4/m^2 and 2.0/m^2) were greatest on the SW and SE quadrants at the end of 17 months. These are the quadrants on reef # 1 with the high and rugged coral growth

The percent urchin density (Figure 10) declined rapidly in the SW quadrant from initial placement of urchins on 09/04 (93% on 09/08/01) through 11/09/01 (43% on 11/09), but then rapidly increased back up to 73% on the 02/26 count. Despite receiving the lowest number of translocated urchins (71, 3.0/m^2), the percent density (47% at the end of 17 months, Figure 10) in the SW quadrant remained considerably higher than the other quadrants and higher than the total density on the reef. Percent urchin density on the SE quadrant was also greater than that on the total reef while quadrants NE and NW were below the density on the total reef (Figure 10).

Although some movement into the SE and especially the SW quadrants seems to have occurred (Figure 10), in general, a gradual and similar decline in urchin densities on the SW and NW quadrants is indicated while urchin densities on the NE and SE quadrants did not decline and even slightly increased from 08/08 to 11/30 (Figures 8 and 10). Between 11/30/02 and 02/05/03, however, density on the SW quadrant increased while density on the NE quadrant declined by about the same amount. A departure from this picture of gradual decline or little change in the density of urchins on each quadrant after 02/26/02 is evident in marked decline in density in the NE quadrant that occurred between the 05/29 (2.2/m^2) and 08/08 (1.2/m^2) counts. This quadrant contains the sheltered site within a large coral structure that was occupied by both large Atlantic burrfish and this quadrant may have been a focus for predation during that time.

In general, the pattern of distribution and changes in density of the urchins on reef # 1 over the course of the study shows a tendency for accumulation of urchins in the SW and SE quadrants, especially in the SW quadrant, and a greater loss or movement out of the NW and to a lesser degree the NE quadrants (Figure 10). The urchins are probably attracted to the high relief and rugged coral formations of the SW and SE quadrants, and/or have better survival in these areas.

Reef # 2

The data on placement and count of urchins on each quadrant of reef # 2 over the course of the project is summarized in Table 4 and 6 and in Figures 9 and 11. Reef # 2 is more homogenous in reef structure than reef # 1. There are no large, complex coral structures on reef # 2, and the coral structures that are present have low relief. Considerably fewer *Diadema* urchins were translocated to reef #2 and they were distributed more evenly over the quadrants of reef # 2, (2.9/m^2 on NW, 3.5/m^2 on NE, 2.6/m^2 on SW, and 3.8/m^2 on SE) than those placed on reef # 1. Density of urchins was always less on reef # 2 than on reef # 1 (Figure 6) with the closest density, 1.4/m^2 on reef # 1 and 1.2/m^2 occurring on the 08/08/02 count.

Within the first 15 days or so there was strong movement of the translocated urchins into the NW, and in the first 3 days, especially into the SE quadrant of reef #2. Although relatively few urchins were released on this reef (85) in the first translocation on 09/04 and 05/01, and no further urchins were placed on the reef until 09/19, the density of the population of the SE quadrant increased to 140% of the density at release on 09/08 (3 days after release), and then declined to 120% on 09/19 (14 days after release). The population on the NW quadrant was 88% of the release density on 09/08, but then climbed to 120% of the release density on 09/19. In contrast, the population density of the NE and SW quadrants were relatively static at 80% and 70% of the release densities over the period from 09/08 to 09/19. In actual numbers, these figures represent a gain of 7 urchins to the SE quadrant and a loss of 1 urchin to the NW quadrant between 09/05 and a loss of 5 urchins to the SE quadrant and a gain of 6 urchins to the NW quadrant between 09/08 and 09/19. Some urchins did move, however, after first release on this reef from the NE and SW quadrants to the NW and SW quadrants very soon after translocation.

In general, after the 10/24 count, the density of the urchin populations declined gradually at a similar rate on all quadrants throughout the course of the study. A notable exception, however, is a rapid loss of density in the NW quadrant ($1.6/m^2$ to $0.8m^2$) from 11/09 to 12/20. The NE and SW quadrants also lost density during this period. In contrast, the SE quadrant gained density from 10/24 to 12/20 ($1.1/m^2$ to $2.0/m^2$), an indication that some movement toward the SE quadrant occurred.

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The SE quadrant had by far the greatest number of urchins (27) and greatest density ($1.4/m^2$) at the first count on 09/08/01 and the least number of urchins (8) and least density ($0.4/m^2$) at the count on 11/30/02. However, on the final count on 02/05/03, the number of urchins on the SE quadrant rose from 8 to 20, a gain in density from $0.5/m^2$ to $1.0/m^2$. The addition of 16 urchins to this reef on 10/23/02 as well as movement to this quadrant probably accounts for this gain. After 02/26 the density of urchins on all quadrants of reef # 2 varied from $1.8/m^2$ on the SE quadrant to $1.0/m^2$ on the SW quadrant, but on 11/30/02, 278 days later, the distribution of urchins over the reef was almost equal in all quadrants, from the highest in the NW quadrant of $0.7/m^2$ to the lowest in the SE quadrant of $0.4/m^2$. Between 11/30/02 and 02/05/03 there was a marked decline in density on the NW quadrant ($0.7/m^2$ to $0.3/m^2$) and an increase in density ($0.5/m^2$ to $1.0/m^2$) on the SW quadrant. The decline was even and gradual in the NE and SE quadrants and more variable with opposite peaks and dips in the NW and SW quadrants. The average (mean) density of urchins on each quadrant over the course of the project was very similar in all quadrants (NW was $1.0/m^2$, NE was $1.2/m^2$, SW was $0.9/m^2$, and SE was $1.3/m^2$). Thus in general, the population of *Diadema* on reef # 2 maintained a variable, but generally homogeneous distribution over the reef over the last 12 months of the project. The lack of high relief and rugged coral formations on this reef probably contributed to this pattern of distribution.

Recruitment

There has been considerable speculation on the role, if any, that a population of adult *Diadema* may have in stimulating settlement and/or survival of post larval *Diadema* in the area of the adults through preparation of the substrate (including stimulation of the growth of coralline algae) and/or release of pheromones (perhaps stimulation to begin metamorphosis), or that the adults may directly aid in the survival of newly settled juveniles through protection under the spines of the adults. Three or four small, apparently newly settled *Diadema* urchins were observed on experimental reef # 1 during the course of the study, and on November 30, 2002 we found 6 new juveniles on reef # 1 and 4 on reef # 2. On February 5, 2003 there were 3 small juveniles on reef # 1 and 1 on reef # 2, no juveniles were observed on the control reefs. They were not found in the immediate presence of adults and it was not obvious that the presence of the now adult *Diadema* on these reefs influenced settlement in any way, but the presence of these juveniles is encouraging. These juveniles were included in the count on these dates.

It has been noted that *Diadema* larvae prefer to settle in areas cleared of filamentous algae (Bak, 1985, Lessios, 1995) and this may be the main reason why settlement occurs in the reef crest rubble zones where the coral rock substrate is cleaned of algae by frequent movement and abrasion by high sea states. The rocky substrates of these shallow rubble areas and reef areas with dense populations of *Diadema* are both relatively clear of algal growth. Lessios (1995) reports on extensive research conducted with *Diadema* and other urchins that occupy similar reef environments, in particular *Echinometra viridis*, which competes with *D. antillarum* for food and substrate. Lessios' research showed that high densities of *E. viridis*, which graze the substrate more intensively than *Diadema*, produced areas with greater rates of *Diadema* recruitment than areas with both *E. viridis* and *D. antillarum* and *D. antillarum* alone. Areas with only *D. antillarum*, however, had greater recruitment than areas with no urchin populations. Lessios concluded that lack of recruitment months after the plague was due to extreme paucity of *Diadema* larvae in the waters of the Caribbean.

Our study indicates that on Florida reefs, the presence of adult *Diadema* is, or should be, helpful to the recruitment of juvenile *Diadema*. Many juveniles settle on the shallow rubble areas of Conch and Pickles reefs during late summer and fall of each year. There is an absence, or extreme dearth, of recruits, however, on the deeper patch reefs where our study took place only a mile or so inshore from Conch and Pickles reefs. If some larvae near settlement are present in the waters of Conch and Pickles reefs, which they must be, then there should also be some larvae present that could, and probably do, settle on nearby reefs as well. Small juveniles 1 to 2.5 cm test diameter, translocated to these reefs survived in large numbers for many days after translocation, thus there is nothing intrinsic in the environment of these patch reefs that would prevent significant survival of juvenile *Diadema*, at least not after a test size of 1.5 to 2 cm is attained. In November, 2002, about one year after translocation and maintenance of a pre plague population level of *Diadema* urchins, we observed a number of juvenile *Diadema* urchins that had settled on the experimental reefs. The number of new juveniles was not great, 10 to 12, roughly about $0.07/m^2$, but this demonstrates that *Diadema* post larvae will settle and survive on Florida reefs where populations of adults are present. However, according to the survival data in our study, settlement and survival of about 1.2 *Diadema* urchins per year on each sq. m of reef area is required to maintain a population of about 1 to 2 urchins/m^2 on the patch reefs of our study. Mortality immediately after settlement is probably very high, so settlement of post larval *Diadema* in numbers far greater than $1.2/m^2$ is no doubt necessary to secure survival of 1.2 urchins per sq. m. We feel that the scarcity of *Diadema* recruits on Florida Keys patch reefs is due to both paucity of larvae in the water mass and a lack of proper substrate and/or settlement stimulus on reefs without an adult population. In all probability, however, given the occurrence of scattered individuals and small groups of urchins in various locations on Keys reefs, the scarcity of late stage larvae in the water is a more significant factor in the failure of *Diadema* to repopulate the Florida reefs than the lack of prepared substrate.

An adult female *Diadama* can produce 10 million eggs every month (Levitan, 1988) and Tom Capo (personal communication) in rearing experimentation with *Diadema* reports the fecundity of some individuals at 15 to 20 million eggs per spawn. Thus when *Diadema* were present on most reefs of the Caribbean, Florida, and the Bahamas at densities from about $1/m^2$ up to perhaps $20/m^2$, the larval load of *Diadema* in these waters must have been absolutely immense. (One can only wonder at the changes that must have occurred in the planktonic ecology of these waters upon the abrupt elimination of this immense component of the zooplankton population.) Despite such extraordinary fecundity, small populations of adults scattered widely over reef areas are not capable of producing large numbers of larvae. This is because *Diadema* urchins are sessile spawners, males and female release gametes into the water without physical contact and without regard to proximity of individuals. Thus when males and females are more than about a meter apart, fertilization of the eggs is severely compromised and few viable larvae result. Also, the scarcity of large adults greatly reduces the fecundity of the populations (Levitan 1991).

Thus small populations and widely spaced individuals are not able to produce the numbers of larvae necessary for recovery of populations to pre plague levels. Natural recovery of dense, pre plague *Diadema* populations will depend on the chance coalescence of many factors that are very favorable to successful settlement and survival of larvae. And it will be necessary for these factors to merge frequently in order to maintain established populations.

Growth

Growth rates of *Diadema* urchins under natural conditions depend on many factors including genetics, temperature, water quality, reef structure, and quantity and quality of benthic algal communities. Accurate determination of the growth rates of *Diadema* urchins under well defined natural conditions would require tagging of a significant number of individual urchins, probably at least 30, and frequently and accurately measuring the test diameter of each urchin over an extended period, at least 6 months to a year. Repeating these experiments under differing conditions of depth, benthos, and seasonality would also be necessary to characterize variability of growth rate potential for this species in various locations.

Although we were not able to conduct such detailed experimentation on growth, we did make estimates of the size range of the *Diadema* urchins collected and translocated to the experimental reefs. Table 1 lists the size ranges of the collected urchins, 249 (34%) were in the small range (1 to 2.5 cm), 306 (41%) were in the medium range (2.6 to 4.9 cm), and 186 (25%) were in the large range (4.5 to 6 or more cm). This collection data illustrates that by far the large majority of the translocated urchins were young juveniles of small test diameter since 75 % had a test diameter of less than 4 cm. Very few were larger than 4.5 to 5 cm. We noticed during the December 20, 2001, population evaluation that very few, if any, of the urchins observed on that count were in what we had defined as the small and medium size ranges at translocation. Although it is possible that the smaller sized urchins sustained the greatest mortality due to predation, it is unlikely that all the smallest urchins would have been lost and only the larger ones survived during the first three to four months. Survival rates at the December 20, 2001, count were 46% on reef # 1 and 45 % on reef # 2, so many of the urchins in the small and medium size ranges must have survived to that point. Thus we feel confident that many of the small urchins in the 2 cm test size range grew to test diameters of 3.5 to 4 cm within the first 4 months. Also, the benthic survey by NURC (Appendix 1) showed that by far the greatest test size range of *Diadema* urchins found on the experimental reefs in September 2001 were in the 4.0 to 4.9 cm range. So, in general, *Diadema* urchins on Upper Keys offshore patch reefs appear to attain a test size of 4 to 5 cm within about one year. Forcucci (1994) reported a growth rate of over 4 mm per month for juveniles with test diameters up to 24.0 mm, and our observations roughly agree with this rate for urchins in the 2.0 to 4.0 cm test diameter range. In general, *Diadema* achieve a test diameter of about 3 to 4 cm within the first year and about 4 to 5 cm in the second year, and a low estimate of longevity is 4 years with a test diameter of about 10 cm (Ogden and Carpenter, 1987).

Benthic ecology

One of the most important facets of this study was to document the changes that may take place in the benthic ecology of the reef due to the presence of a large population of *Diadema* urchins. This aspect was undertaken by the National Undersea Research Center (NURC) based on Key Largo, FL. Mark Chiappone, Dione Swanson, and Steven Miller of this institution conducted a Rapid Assessment protocol on the experimental and control reefs before translocation of the Diadema urchins (08/31/01, 09/1/01) and about one year after translocation (09/18/02). The initial NURC report is part of the first interim report on this project, Appendix 2 and the second report comparing the before and after analysis of the benthic ecology of the four reefs is included as Appendix 1. Please refer to Appendix 1 for the detailed analysis of ecological changes on the experimental reefs and a scientific account of the history and ecological background of *Diadema* urchins in the broad Caribbean region.

Over the course of this study, the average (mean) density of *Diadema* urchins on both experimental reefs $1.6/m^2$ on reef # 1 and $1.0/m^2$ on reef # 2, an average density of about $1.3/m^2$. These densities were considerably less than historical maximum densities of 4 to 5 per sq. m reported for some areas of the Florida Keys (Chiappone, et. al, 2002), although overall *Diadema* urchin densities on Florida Keys reefs may have been closer to 1.0 (Chiappone, et. al. Appendix 1). Despite the persistence of densities of only 1 to 2 urchins per sq. m and the relatively brief period of the study, only one year, significant ecological changes occurred on the experimental reefs during the course of this study. Briefly, these are the most significant changes that occurred in the benthic ecology of the experimental reefs during the course of this study.

1. Percent stony coral cover increased on the experimental reefs from 9.8% to 15.3% (+ 56% relative increase) and decreased on the control reefs from 9.1% to 6.8% (-26% relative decrease).

2. Sponge cover decreased on the experimental reefs from a mean of 7.4% to 5.3% and increased on the control reefs from 5.3% to 6.0%.

3. Algal turf cover decreased slightly on the experimental reefs from 28% to 24% (-16.2% relative decrease) while algal turf increased on the control reefs from 23.4% to 27.8% (+18.7% relative increase).

4. Crustose coralline algae exhibited the most significant change. Coralline algae cover increased on the experimental reefs from 7.5% to 19% (+ 153% relative increase) while coralline algae cover decreased on control site 1 (reef # 3) and slightly increased on control site 2 (reef # 4), a total change of 7.8% to 8.8% (+ 6.5% relative increase) on the control sites. The presence of crustose coralline algae has been shown to stimulate settlement of certain species of stony corals.

5. Green calcareous algae (mostly *Halimeda* spp.) showed little change on the experimental reefs (a decline from 3.8% to 3.1%), but increased on the control sites (an increase of 1.8% to 3.8%).

6. Brown foliose algae, mostly *Dictyota* spp., greatly declined on the experimental reefs a decrease of 10% to 5.1%, a – 48% relative decrease) and increased slightly on the control reefs (an increase of 4.5% to 5.9%, a + 31% relative increase). Interestingly, brown foliose algae declined on experimental reef # 1 to a remarkable extent (11% to 1.8%, a – 511.1% decrease), and also declined on control reef # 4 (which hosted a small population of *Diadema* urchins) from 3.0% down to 1.0%. Experimental reef # 2 showed a small decrease in brown foliose algae from 9.0 to 8.5%, while control site 1 (reef # 3) showed an increase in brown foliose algae from 6.0% to 10.8%. Brown foliose algae are important competitors with corals for space and sunlight, and removal of these algae from the reefs is critical to coral recovery.

7. The density of juvenile corals increased on the experimental reefs from an average of 6.2 juveniles/m^2 to 15.3 juveniles/m^2, a relative increase of + 147%. Average (mean) densities also increase on the control sites (reefs # 3 and # 4) but to a lesser degree, 6.6 juveniles/m^2 to 9.9 juveniles/m^2, a relative increase of +51%. The NURC summary on the presence of juvenile corals on the experimental and control reefs stated "Thus, for some of the more common species (corals) observed as juveniles, while greater numbers of smaller size classes were observed in 2002 compared to 2001, these changes were magnified on the experimental patch reefs."

These are all positive changes showing a marked reduction in algal prevalence and signifying a return to a coral dominated ecology. These changes in the ecology of the experimental reefs are what was expected from a return of *Diadema* urchins to the reefs, and reflect the changes that have occurred on limited areas of Caribbean reefs where populations of *Diadema* have returned naturally.

Discussion

There were four specific biological restoration objectives in this project. We feel we have succeeded in attaining these objectives to a large degree during the conduct of this project. Each of these objectives is listed below with a brief comment on what this study has revealed on these topics.

1. Determine if *Diadema* urchins survive transplantation and the size that exhibits the best survival rate after transplantation.

Diadema urchins certainly survive transplantation. The initial survival rates of 80 to 90 percent over the first few weeks after translocation and continued survival at levels of about 1.0/m2 over the entire year of the project demonstrate that adequate survival of translocated *Diadema* urchins is attainable. We were not able to definitively determine the best size for translocation, but the indications are that the larger urchins, test size greater than 2 cm, survive better than the smaller urchins.

2. Estimate the survival rates and the growth rates of transplanted *Diadema*.

Survival rates on each experimental reef and on each quadrant of each reef were carefully analyzed. The initial high loss rates (mortality) over the first two to three months leveled off at about 50% and over the last 12 months of the study, survival dropped to about 25%. Density (number of urchins per sq. m), however, were maintained at about 1 to 2 per sq. m on both experimental reefs throughout the sturdy. The daily rate of percent reduction in density of urchins on both reefs after the first two months was exactly the same. Over the 9 month period between the counts of, 02/26/02 to 11/30/02, the density of urchins declined $0.9/m^2$ on both experimental reefs; a daily rate of loss of density of about 0.0032 urchins/m^2 on both reefs. Thus to maintain a population of *Diadema* urchins at a density of about $1/m^2$ on a reef area, a recruitment rate that would support survival of about 1.17 urchins per sq. m of reef area per year would be required.

It is tempting to speculate that translocation of *Diadema* urchins on Florida Keys reefs, especially larger urchins, should be targeted at densities of about $2m^2$. Densities greater than $2/m^2$ may experience undue loss and densities less than $1/m^2$ may be too few to establish persistent and biologically effective populations. This speculation is based more on intuition and experience rather than analysis of data. Also, Lessios (1995) reports that the average density on all reefs censussed in the San Blas area off Panama in the Caribbean before the plague was close to $1.0/m^2$. However, population densities much greater than $1/m^2$ were not uncommon in the Caribbean. Bak (1985) reported that densities of *Diadema* along the southwest coast of Curacao had urchin densities of 4 to

12 *Diadema* per sq. m during the period 1975 to 1983. Although populations much greater than $1.0/m^2$ have been reported, healthy populations over broad areas containing varied types of reef structure and hard bottom in the Florida Keys may have a climax density of about $1.0/m^2$. The various types of reef structure present in Florida Keys reefs, various exposures to predation, and perhaps most important, varied incident of recruitment may greatly affect the density of urchins on specific reef areas in various locations. Research on the response of urchin populations translocated to various reef types and locations is needed.

Estimates of growth rates observed in this study indicate that only about 4 to 6 months are required for juveniles (1.5 to about 2.0 cm test diameter) to attain a small adult size of 3 to 4 cm test diameter.

3. Determine the distribution patterns that *Diadema* urchins develop on the test reef. (They will be placed initially in protected microhabitats within the reef structure and this initial distribution will be recorded on maps of the patch reefs.)

The distribution patterns of *Diadema* on these patch reefs are indicated by the data on the density of populations of urchins on the four quadrants of each experimental reef. In general, although there was movement of urchins from quadrant to quadrant, and indications of concentration in quadrants with high and complex coral formations, for the most part, the urchins remained relatively evenly distributed over all the quadrants of each experimental reef.

4. Compare and contrast general reef condition and community level changes, including coral recruitment and growth, on the manipulated and reference reefs over time."

The before and after benthic assessments by NURC demonstrated that, among other positive changes on the experimental reefs, algal cover is markedly decreased, coralline algae cover markedly increased, stony coral cover increased, and the density of juvenile corals increased significantly over that of the control reefs.

Control site # 2 (reef #4) was selected, even though it was smaller in area than the other reefs (about 44 sq. m, less than half the size of experimental reef # 1 at 100 sq. m) because it had similar coral structure to reef # 1. The control to reef # 1 was flawed, however, because a small population of mature *Diadema*, about 6, was found on this reef during the mapping procedure (and observed in both NURC assessments of this reef). The presence of these urchins and the smaller size of the reef reduced the accuracy of the comparison of this control reef # 4 to the experimental reef # 1. This is especially reflected in the pattern of brown foliose algae cover in the NURC analysis. The percent cover of brown foliose algae on experimental reef # 1, which had no *Diadema* urchins in resident at the beginning of the project in 2001, was 11.0% while control reef # 4 with about 6 large *Diadema* (and a much smaller total reef area) had a brown foliose algae cover of only about 3.0%. Brown foliose algae cover declined on experimental reef #1 during the year of the experiment to 1.75 %, and also declined on control site # 2 (reef #

4) from 3.0% to about 1.0 %. In contrast, brown foliose algae on control site # 1 (control reef # 3) increased during the course of the study from 6.0% to 10.75%. Despite the weak experimental/control relationship between reefs 1 and 4, as stated in the NURC report in Appendix 1, "Overall the coverage of brown foliose algae on experimental sites decreased from 10% to 5.1%, representing a –4.9% absolute decline and –48% relative decline. In contrast control sites either exhibited no change or an increase in coverage of brown foliose algae (Table 9)."

In contrast to experimental reef # 1, percent cover of brown foliose algae decreased only slightly, from 9% to 8.5%, on experimental reef # 2. However, on control site #1 (control reef # 3), a reef quite similar to experimental reef # 2, brown foliose algae increased from 6% to 10.75% over the year of the study. A lower average density of urchins on experimental reef # 2, 1.1/m^2 than on experimental reef # 1, 1.7/m^2, may have permitted greater algal growth on reef # 2.

Diadema are relatively immobile during the day and move about as they feed at night. They may return to a particular sheltered area during the day or may simply find an adequate shelter as dawn approaches. At the beginning of the project we observed a particular juvenile that had apparently settled naturally and that occupied a specific small cavity in a rock structure on the SE quadrant of reef # 1over a period of several months. This indicates that at least juveniles tend to remain in the same area and occupy the same shelter during the day. Large adults probably have a greater range and may occupy various sheltered areas during the day.

The show that in this study, once *Diadema* urchins attained an adult size of about a 4 cm test diameter and above, mortality rates declined to slightly less than 1.0 urchins per sq. m per year, a rate of about 0.0025 urchins per sq. m per day.

A major concern on repopulation of *Diadema* on Florida reefs is the potential for the return of the plague organism that decimated populations of these urchins in 1983-84. This is a real concern, especially since there was a secondary mortality of *Diadema* in 1990-01 (Forcucci (1994). The mortality caused by this plague organism is rapid and affects almost all urchins within a very broad area. The mortality we observed on the experimental reefs during this study was gradual and persistent, but affected only a relatively small number of urchins at any one time. We also never observed the disintegration of urchins leaving a mass of disarticulated tests and spines, thus the plague apparently did not cause urchin mortality during our study.

Predation was evidently the major cause of mortality of the urchins on the experimental reefs. We directly observed predation on the urchins by the Atlantic burrfish, *Chilomycterus atinga*, and other predators such as triggerfish, hogfish, permit, grunts, spiny lobsters, and spider crabs may have also actively preyed on the urchins, especially on small juveniles, but active predation by other predators was not observed during our study. Such predators once accustomed to feeding on *Diadema* urchins and upon finding a relatively dense population, may quickly remove a significant number of urchins from a dense population before moving on to other areas. Without consistent recruitment adequate to maintain an effective population, these small isolated populations dwindle in number over a period of months to years. Populations of *Diadema* that occur in areas with some protection from predators, such as shallow protected areas or rugged and complex reef areas may better resist predation and persist in numbers over a longer period time. Also, very low levels of recruitment would be more effective in maintaining populations in such areas.

Restoration

The importance of healthy populations of *Diadema* to the coral reefs of the Florida Keys cannot be overstated. The following summation by Ogden and Carpenter (1987) based on over 20 years of experiments and observations is a strong testimony to the need for restoration of this species.

"Through direct effects on algal communities or indirect effects on other benthic reef organisms, grazing by *Diadema* is a major factor controlling the community structure of coral reefs. ….. perhaps no other single species in the coral reef environment has such profound effects on the other organisms composing the reef community."

The major underlying purpose of this study was to explore the results and possibilities of restoration of *Diadema* urchins to the reefs of the Florida Keys. As noted in the literature for Caribbean reefs, and as demonstrated in this study, the benthic ecology of coral reefs shifts away from dominance by macro algae back toward dominance of coral growth relatively quickly after populations of *Diadema antillarum* at densities of about $1/m^2$ are present on the reefs. It is obvious that the reefs of the Florida Keys would benefit immensely from restoration of *Diadema* urchins to reef areas. Restoration may occur naturally, there are indications that some recovery is occurring in isolated areas of the Caribbean, Jamica , Beleze, and other areas, and even some small areas in the Dry Tortugas have populations of large urchins about two years old that were in densities of 0.4 to 0.8 urchins per sq. m (NURC, 2001). These remote populations are probably the source of the recruits that appear on the rubble zones of Keys reefs in the late summer and fall months.

Restoration of *Diadema*, however, has not occurred in the 20 years since the plague mortalities of 1883-4, and very low larval densities and extensive predation on juvenile and adult urchins may prevent (Lessios, 1995) or greatly delay natural restoration of pre plague densities of this species. Our study demonstrates that a program of continuous movement of juveniles from settlement on reef crest rubble zones to specific deeper reef areas can establish and maintain relatively dense populations of *Diadema* in small reef areas. The continuous placement of juvenile urchins on these areas after initial translocation of a population of about $2/m^2$ at a rate of about $1/m^2$ per year would substitute for natural recruitment and maintain a reproductively effective population. This would serve two purposes. First, to restore small reef areas, perhaps in Marine Protected Areas, to a coral dominated ecology that will allow settlement and growth of corals under historical environmental conditions, which would be an important research tool and a reservoir of natural coral growth. And second, it would establish small populations of reproductively active *Diadema* that will increase the density of larval *Diadema* in the waters downstream of these populations. The immense fecundity of adult female *Diadema* greatly enhances the importance of even small populations of reproductively active adults. Such translocation and monitoring programs would not be expensive and could be done with volunteer personnel, and could be instrumental in aiding the recovery of this keystone herbivore to the reefs of the Florida Keys.

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Table 1. Collection data for juvenile *Diadema antillarum* at Pickles and Conch reefs.

Date 2001	Conch	Pickles	small 1 – 2.5 cm	medium 2.6 – 4.0 cm	large 4.5 – 6+ cm	effort in collector hours
09/04		162	43	102	17	6.0 hrs
09/05		123	23	93	7	6.0 hrs
09/17	11			11		0.5 hrs
09/19	75		58	13	4	2.0 hrs
09/21	105		32	33	40	6.0 hrs
09/26	78		53	14	11	1.5 hrs
10/05	41		15	5	21	1.5 hrs
10/24		55	22	14	19	2.0 hrs
12/14	17		1	6	10	0.5 hrs
12/20	74		2	15	57	4.0 hrs
Totals	401	340	249	306	186	30.0 hrs

Table 2. Translocation and survival data of *Diadema antillarum* on two experimental Reefs, 09/4/01 to 11/30/02.

Date	Experimental Reef # 1 (96 m^2)				Experimental Reef # 2 (88 m^2)			
	total released before count	total count	% survival (#C/#R)	# released this date (after count)	total released before count	total count	% survival (#C/#R)	# released this date (after count)
09/04,5				201				85
09/08	201	160	80		85	79	93	
09/17				11				
09/19	212	172	81		85	79	93	27
09/21								105
09/26				79				
10/05				42				
10/24				34	217	134	62	21*
11/09	367	161	44		238	118	50	
12/14				17				
12/20	384	175	46	50	238	106	45	24
02/26	434	202	47		262	122	47	
05/29	434	181	42		262	109	42	
08/08	434	135	31		262	103	39	
10/08	434	122	28		262	77	29	
10/23								16
11/30	434	119	27		278/262	63/47	23/18	
02/05	434	115	26		278	55	20	
Totals				434				278/262**

*The 21 urchins released on this date were included in the count on this date. For this table these 21 urchins were subtracted from the number released and from the number counted.
**The 16 urchins released on 10/23 were not included in data analysis of 11/30.

Table 3. Reef # 1. Number of *Diadema* released, cumulative (#Rel), density released (#/m^2), actual number counted, (Cnt), and number present per square meter (#/m^2) on each quadrant at each population evaluation.

Quadrant	NW 32 sq. m				NE 20 sq. m				SW 24 sq. m				SE 20 sq. m			
Date	#Rel	#/m^2	#Cnt	#/m^2	#Rel	#/m^2	#Cnt	#/m^2	#Rel	#/m^2	#Cnt	#/m^2	#Rel	#/m^2	#Cnt	#/m^2
09/08	70	2.2	56	1.8	45	2.3	36	1.8	37	1.5	34	1.4	49	2.5	34	1.7
09/19	81	2.5	71	2.2	45	2.3	30	1.5	37	1.5	25	1.0	49	2.5	46	2.3
11/09	120	3.8	47	1.5	94	4.7	46	2.3	56	2.3	23	1.0	97	4.9	45	2.3
12/20	127	3.9	43	1.3	99	5.0	44	2.2	56	2.3	35	1.5	102	5.1	53	2.7
02/26	142	4.4	58	1.8	109	5.5	42	2.1	71	3.0	53	2.2	112	5.6	49	2.5
05/29	142	4.4	47	1.5	109	5.5	40	2.2	71	3.0	47	2.0	112	5.6	47	2.3
08/08	142	4.4	34	1.1	109	5.5	23	1.2	71	3.0	40	1.7	112	5.6	38	1.9
10/08	142	4.4	27	0.8	109	5.5	25	1.3	71	3.0	35	1.5	112	5.6	35	1.8
11/30	142	4.4	23	0.7	109	5.5	28	1.4	71	3.0	31	1.3	112	5.6	37	1.9
02/05	142	4.4	19	0.6	109	5.5	21	1.1	71	3.0	35	1.4	112	5.6	40	2.0
mean				1.3				1.7				1.5				2.1

Table 4. Reef #2. Number of *Diadema* released, cumulative (#Rel), density released (#/m^2), actual number counted, (Cnt), and number present per square meter (#/m^2) on each quadrant at each population evaluation.

Quadrant	NW 20 sq. m				NE 24 sq. m				SW 24 sq. m				SE 20 sq. m			
Date	#Rel	#/m^2	#Cnt	#/m^2	#Rel	#/m^2	#Cnt	#/m^2	#Rel	#/m^2	#Cnt	#/m^2	#Rel	#/m^2	Cnt	#/m^2
09/08	15	0.8	14	0.7	25	1.0	18	0.8	25	1.0	20	0.8	20	1.0	27	1.4
09/19	15	0.8	20	1.0	25	1.0	19	0.8	25	1.0	17	0.7	20	1.0	23	1.2
10/24	53	2.7	30	1.5	58	2.4	46	1.9	55	2.3	36	1.5	51	2.6	22	1.1
11/09	57	2.9	32	1.6	65	2.7	37	1.5	58	2.4	17	0.7	58	2.9	32	1.6
12/20	57	2.9	15	0.8	65	2.7	32	1.3	58	2.4	20	0.8	58	2.9	39	2.0
02/26	57	2.9	25	1.3	75	3.1	38	1.6	62	2.6	24	1.0	68	3.4	35	1.8
05/29	57	2.9	30	1.5	75	3.1	31	1.3	62	2.6	20	0.8	68	3.4	28	1.4
08/08	57	2.9	19	1.0	75	3.1	31	1.3	62	2.6	28	1.2	68	3.4	25	1.3
10/08	57	2.9	12	0.6	75	3.1	24	1.0	62	2.6	21	0.9	68	3.4	20	1.0
11/30	57	2.9	14	0.7	75	3.1	14	0.6	62	2.6	11	0.5	68	3.4	8	0.5
02/05	57	2.9	5	0.3	83	3.5	15	0.6	62	2.6	15	0.6	76	3.8	20	1.0
mean				1.0				1.2				0.9				1.3

Table 5. Reef # 1. Percent change in density (% Sur, apparent survival) of *Diadema* (#/m^2 counted / #/m^2 released) on each quadrant and on the total reef area, including density released (R#/m^2) and counted (C#/m^2) on the total reef area.

Quadrant	NW	NE	SW	SE	total reef area		
	32 sq. m	20 sq. m	24 sq. m	20 sq. m	96 sq. m		
Date	% Sur	% Sur	% Sur	% Sur	R#/m^2	C#/m^2	% Sur
09/08	82	78	93	68	2.1	1.7	81
09/19	88	65	67	92	2.1	1.8	82
11/09	39	49	43	47	3.8	1.7	45
12/20	33	44	65	53	4.0	1.8	45
02/26	41	38	73	45	4.5	2.1	47
05/29	34	36	67	41	4.5	1.9	42
08/08	25	22	57	34	4.5	1.4	31
10/08	18	24	50	32	4.5	1.3	29
11/30	16	25	40	34	4.5	1.2	27
02/05	14	20	47	36	4.5	1.2	27

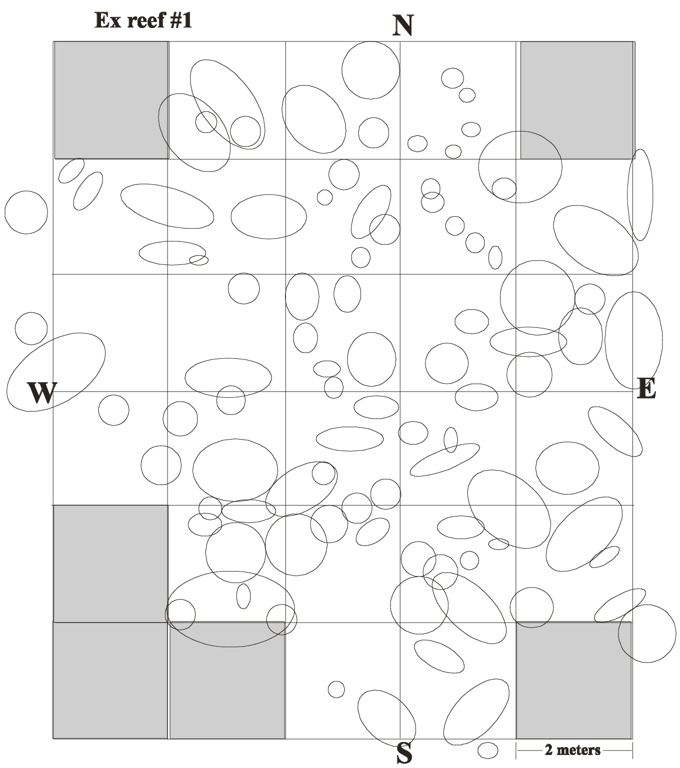
Table 6. Reef # 2. Percent change in density (% Sur, apparent survival) of *Diadema* (#/m^2 counted / #/m^2 released) on each quadrant and on the total reef area, including density released (R#/m^2) and counted (C#/m^2) on the total reef area.

Quadrant	NW	NE	SW	SE	total reef area		
	20 sq. m	24 sq. m	24 sq. m	20 sq. m	88 sq. m		
Date	% Sur	% Sur	% Sur	% Sur	R#/m^2	C#/m^2	% Sur
09/ 08	88	80	80	140	1.0	0.9	90
09/19	125	80	70	120	1.0	0.9	90
10/24	55	79	65	42	2.3	1.4	61
11/09	55	55	29	55	2.7	1.3	48
12/20	28	48	33	69	2.7	1.2	44
02/26	45	52	38	53	3.0	1.4	47
05/29	52	42	31	41	3.0	1.2	40
08/08	34	42	46	38	3.0	1.2	40
10/08	21	32	35	29	3.0	0.9	30
11/30	24	19	19	12	3.0	0.5	17
02/05	10	19	23	29	3.2	0.6	20

Table 7. Reefs # 1 and # 2. Percent rate of loss per day (mortality rate) of *Diadema* urchins on each reef at each count.

Date	Total # of days before each count	Reef # 1 % loss (density) from inception at each count	Reef # 1 % rate of loss per day (%loss/# days)	Reef # 2 % loss (density) from inception at each count	Reef # 2 % rate of loss per day (% loss/# days)
09/05	0	0	0	0	0
09/ 08	3	19	6.33	10	3.33
09/19	14	18	1.29	10	0.71
10/24	49	--	--	39	0.80
11/09	65	55	0.85	52	0.80
12/20	106	55	0.52	56	0.53
02/26	174	53	0.31	53	0.31
05/29	267	58	0.22	60	0.23
08/08	338	69	0.20	60	0.18
10/08	399	71	0.18	70	0.18
11/30	452	73	0.16	83	0.18
02/05	519	73	0.14	80	0.15

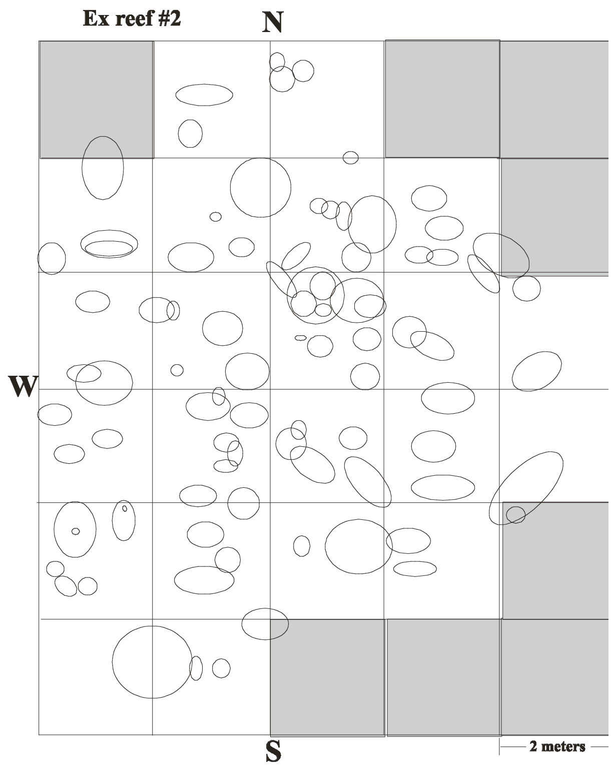
Figure 1. Working map of experimental reef # 1 and # 2.



Placement and approximate size of coral formations on Experimental Reef # 1

Shaded sectors are areas of little or no reef structure that are not included in reef area calculations. 1

N 24.59.177’
W 80.26.099’



Placement and approximate size of coral formations on Experimental Reef # 2

Shaded sectors are areas of little or no reef structure that are not included in reef area calculations. 1

N 24.59.172
W 80.26.108’

Figure 2. Reef # 1: Total Diadema released (cumulative) and counted at each populatio evaluation.

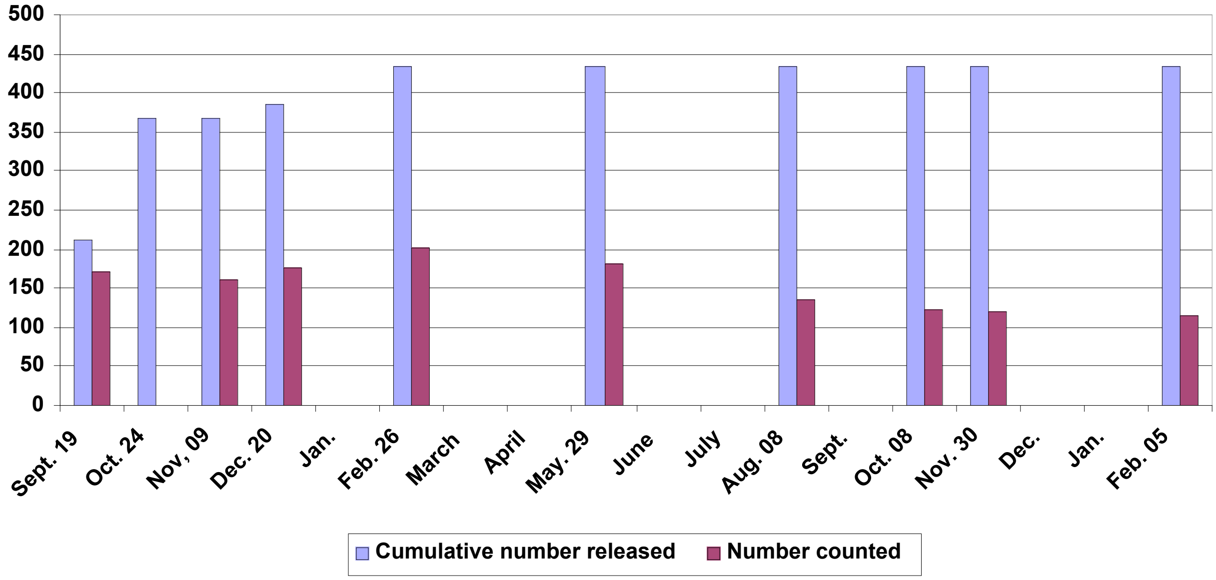


Figure 3. Reef # 2: Total Diadema released (cumulative) and counted at each populatio evaluation.

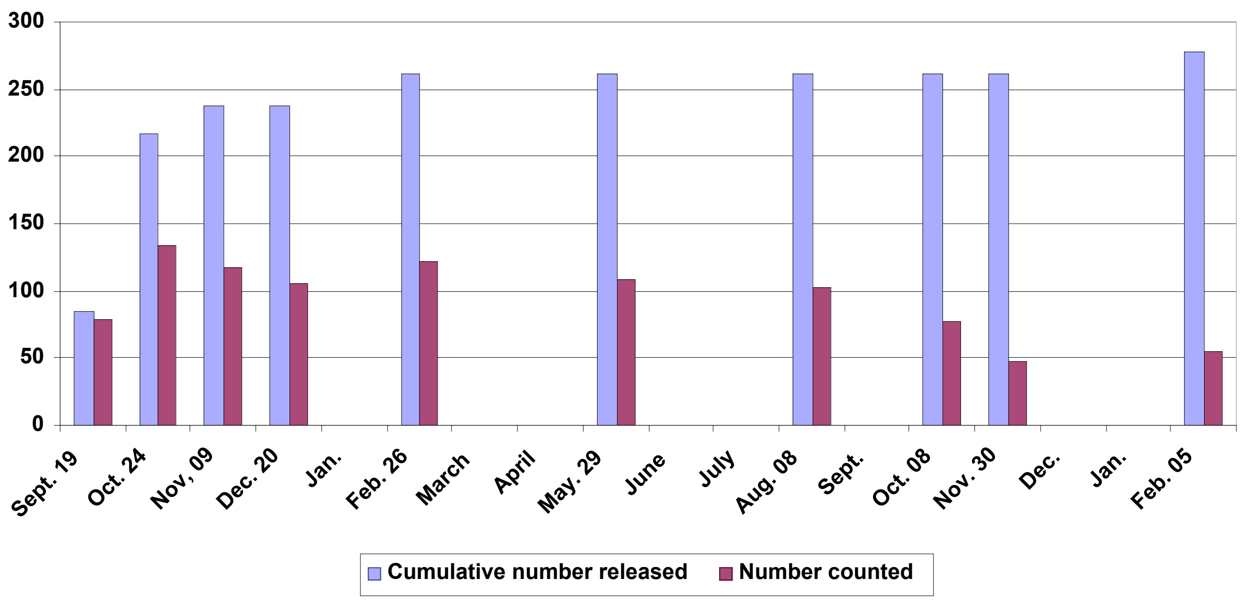


Figure 4. Reefs # 1 & #2: Combined release (cumulative) and count data at each population evaluation.

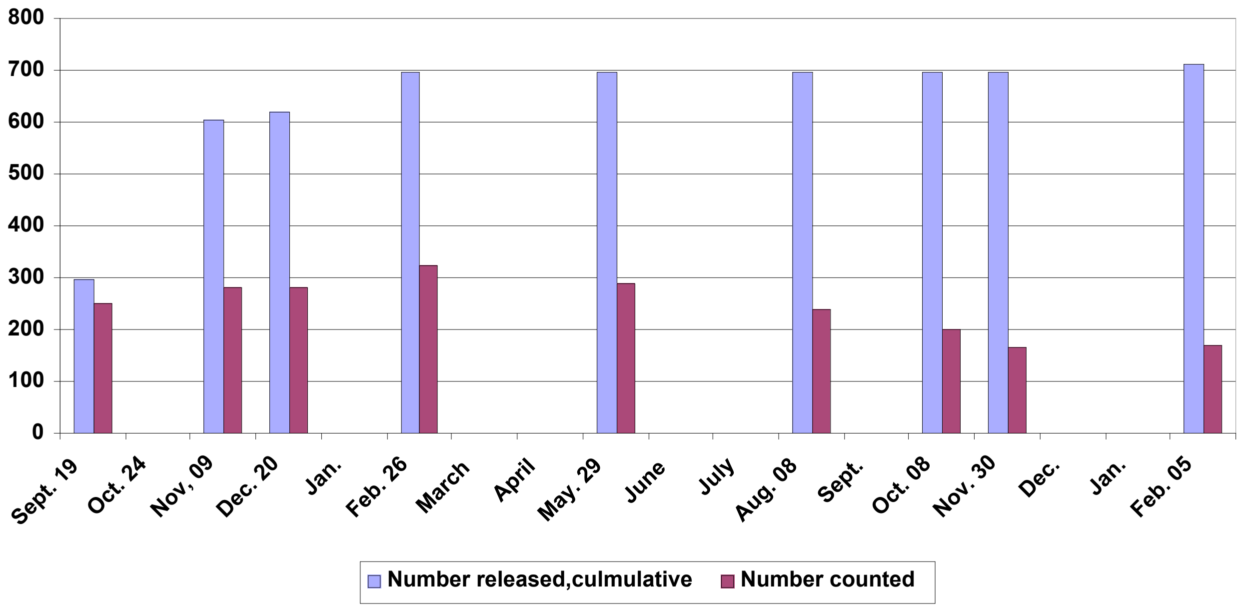


Figure 5. Percent apparent survival of Diadema by density (#/sq. m counted / #/sq. ı released) at each count on reefs # 1 and # 2.

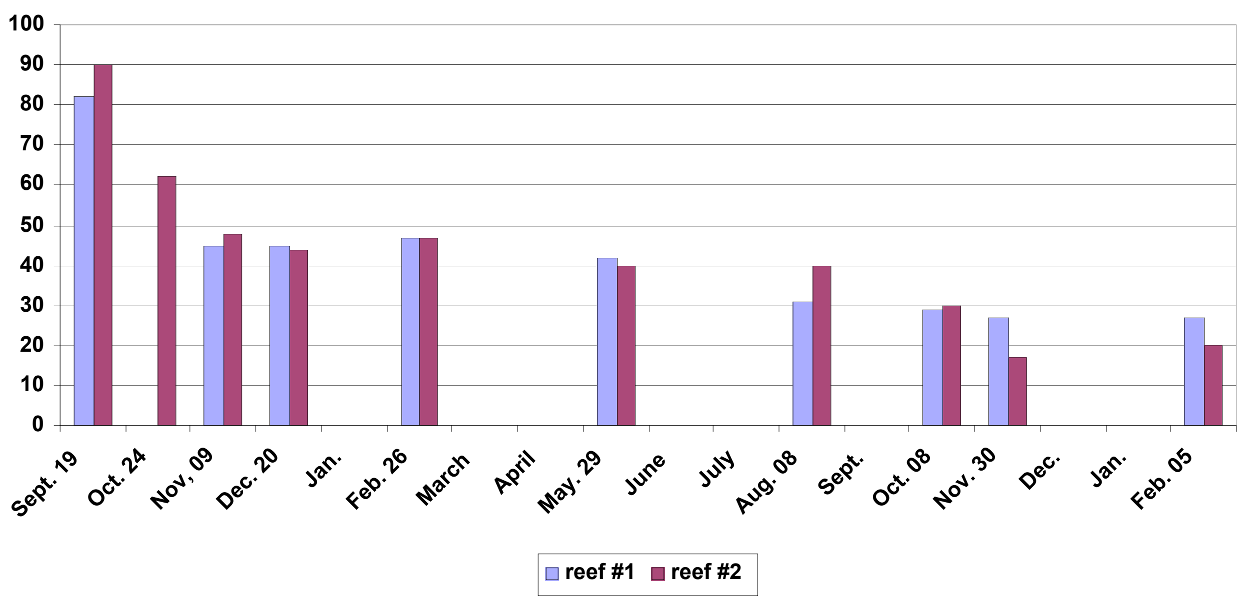


Figure 6. Density (#/sq. m) of Diadema on each experimental reef at each count

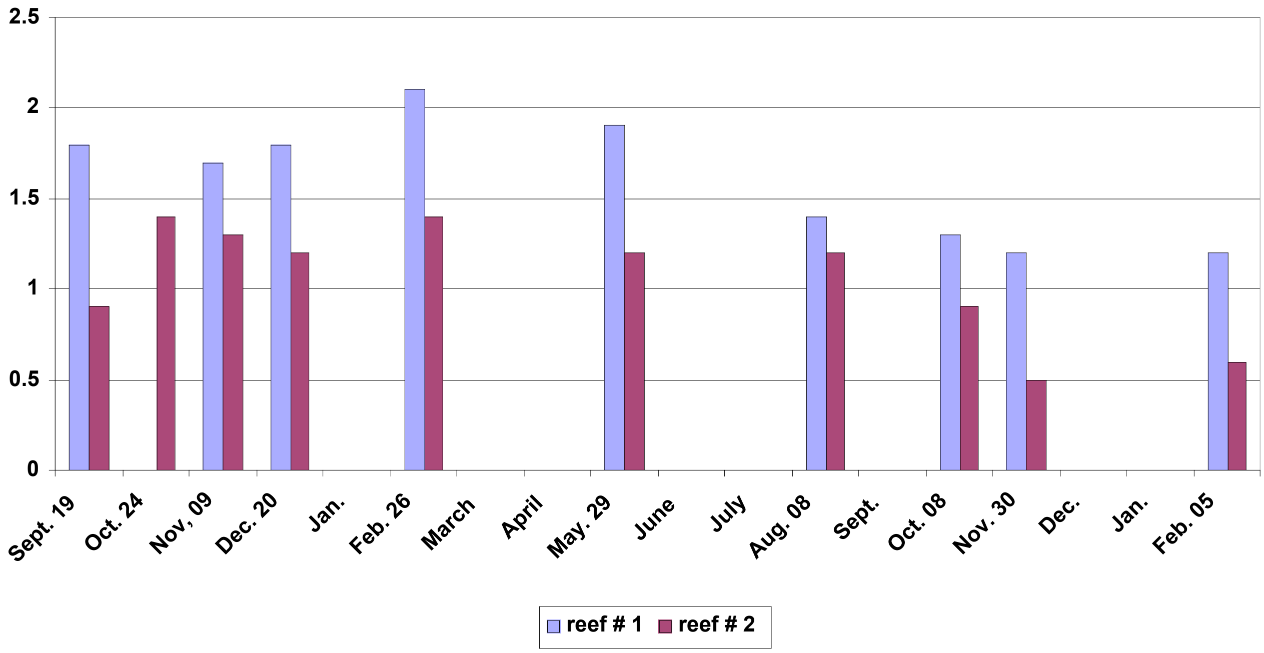


Figure 7. Percent rate of loss per day of total *Diadema* urchins released (daily mortality rate) on each reef at each count.

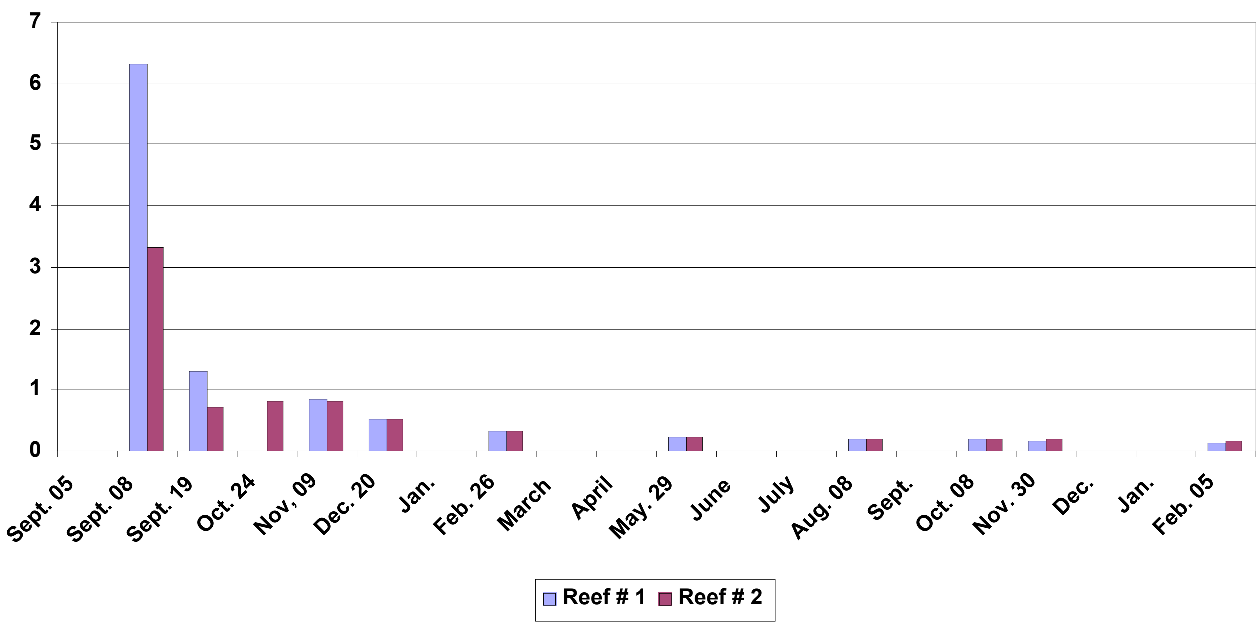


Figure 8. Reef # 1: Density of Diadema urchins (#/sq. m) cumulative total released (R) and number counted (C) on each quadrant at each count.

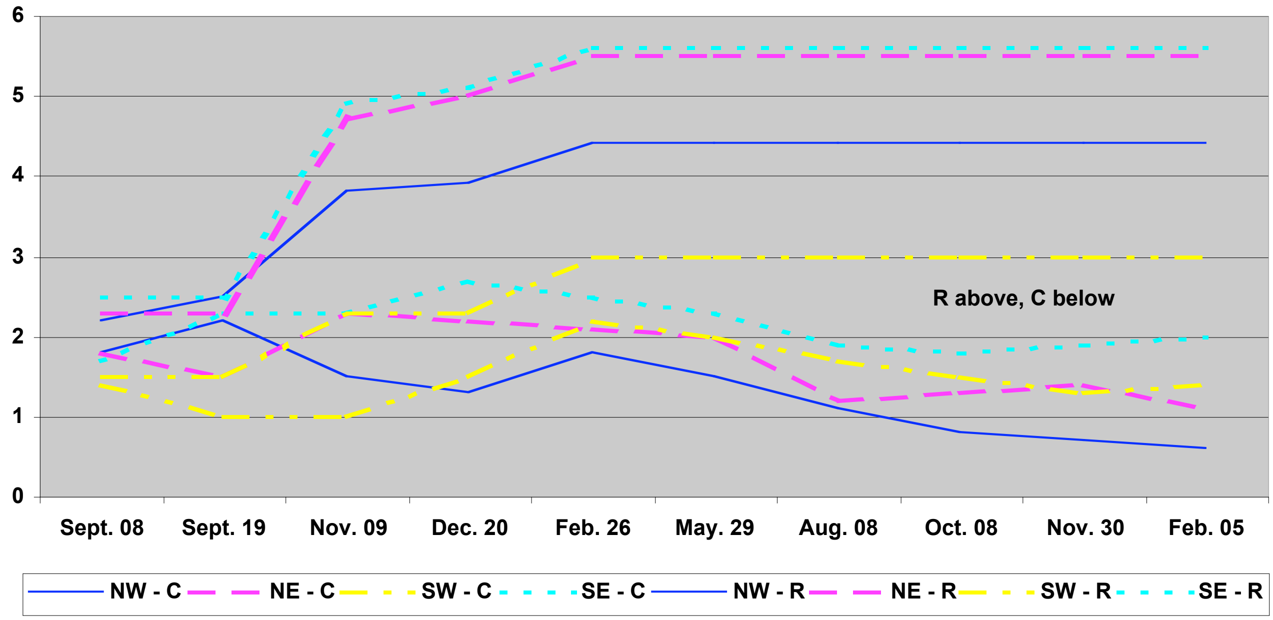


Figure 9. Reef # 2: Density of Diadema urchins (#/sq. m) released (R) and number counte (C) on each quadrant at each count.

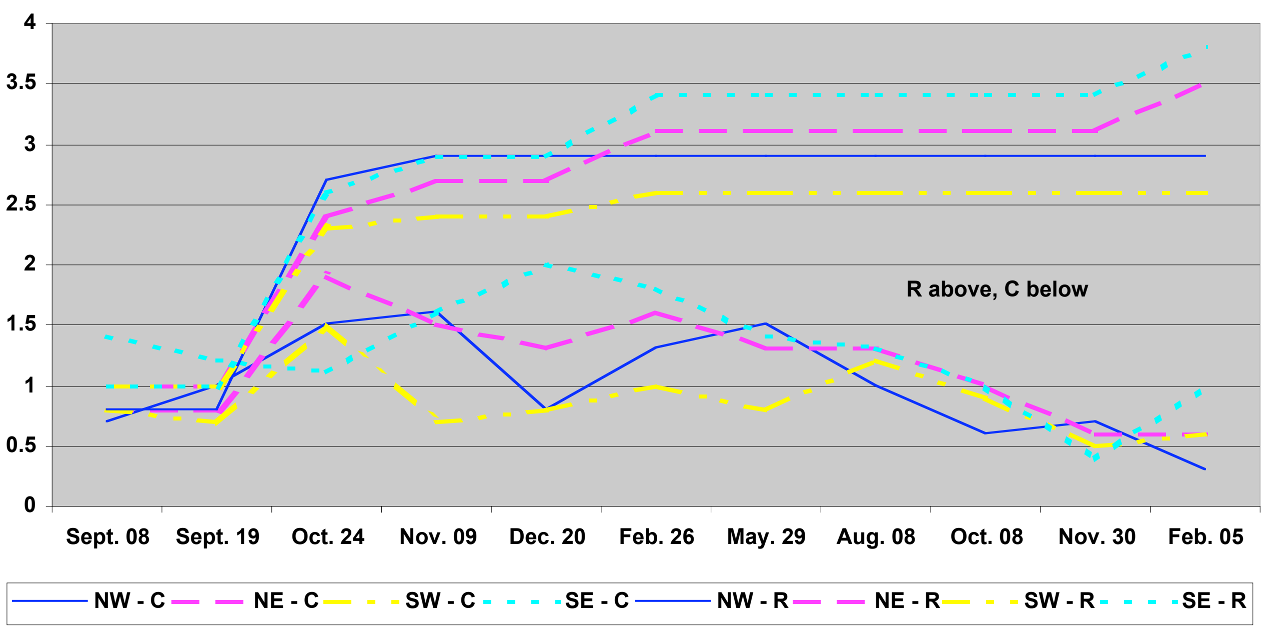


Figure 10. Reef # 1: Percent change in density of Diadema (#/sq. m counted / #/sq. r
released on quadrant and on the total reef area at each count.

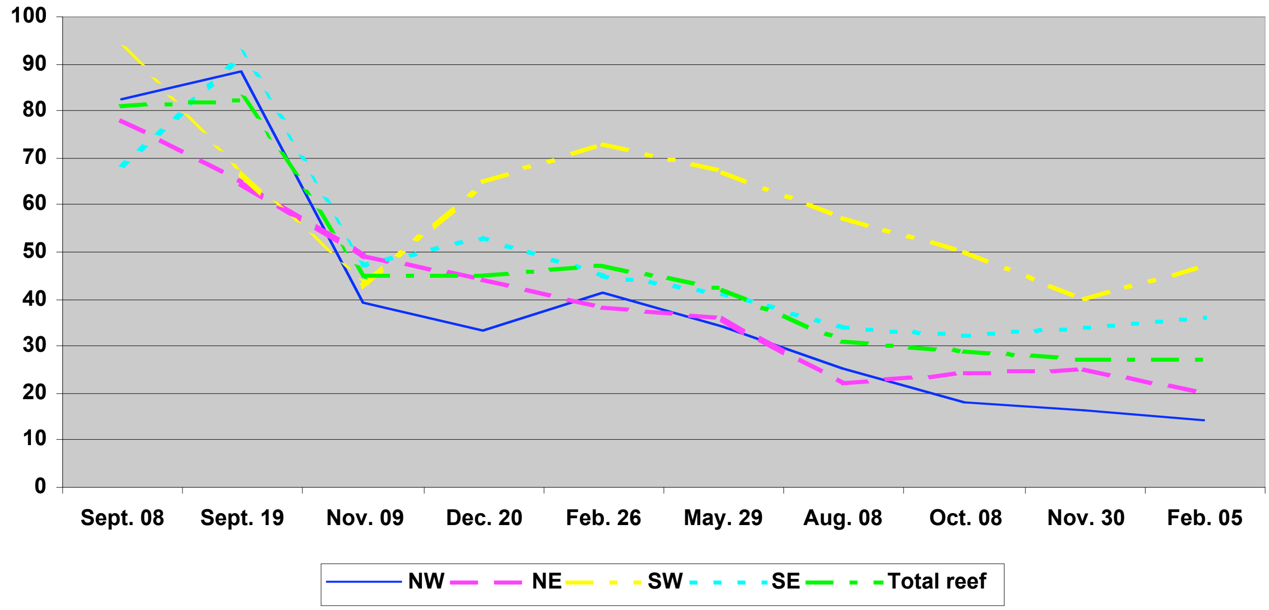
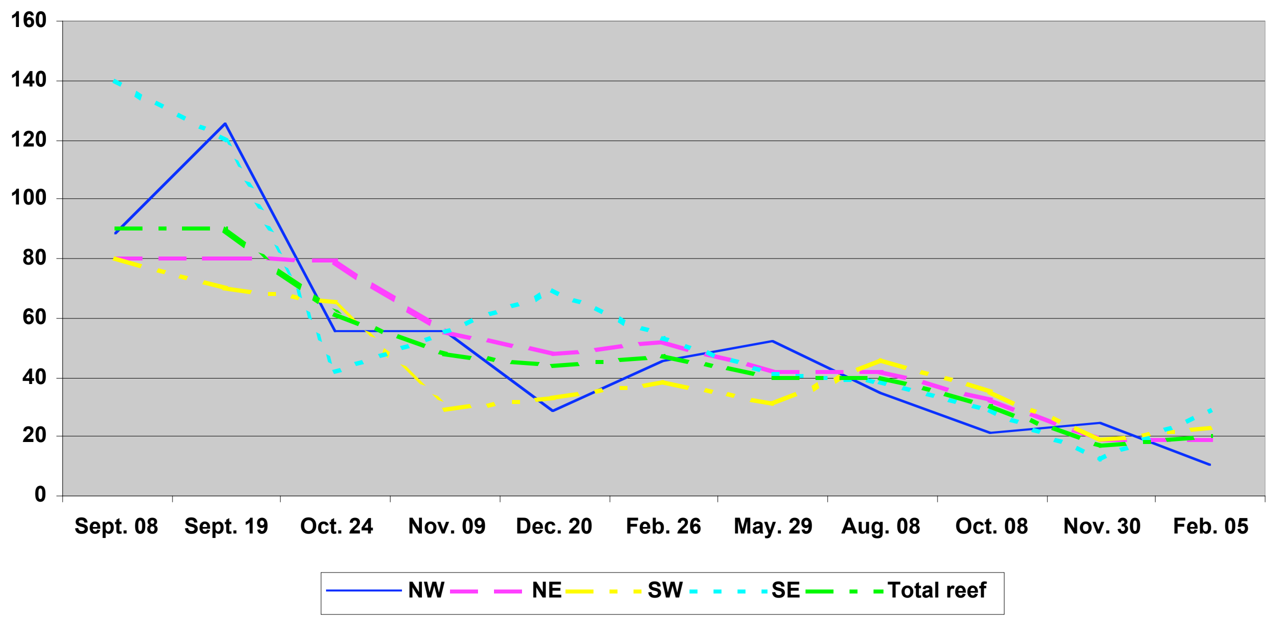
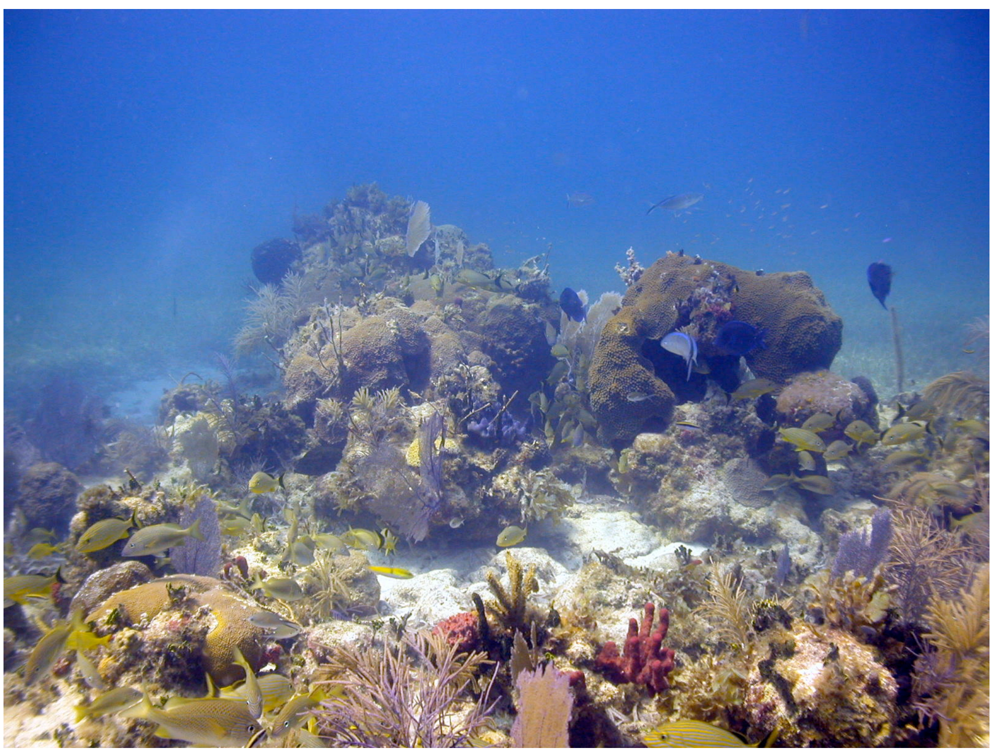


Figure 11. Reef # 2: Percent change in density of *Diadema* (#/sq. m counted / #/sq. m
released) on each quadrant and on the total reef area at each count.

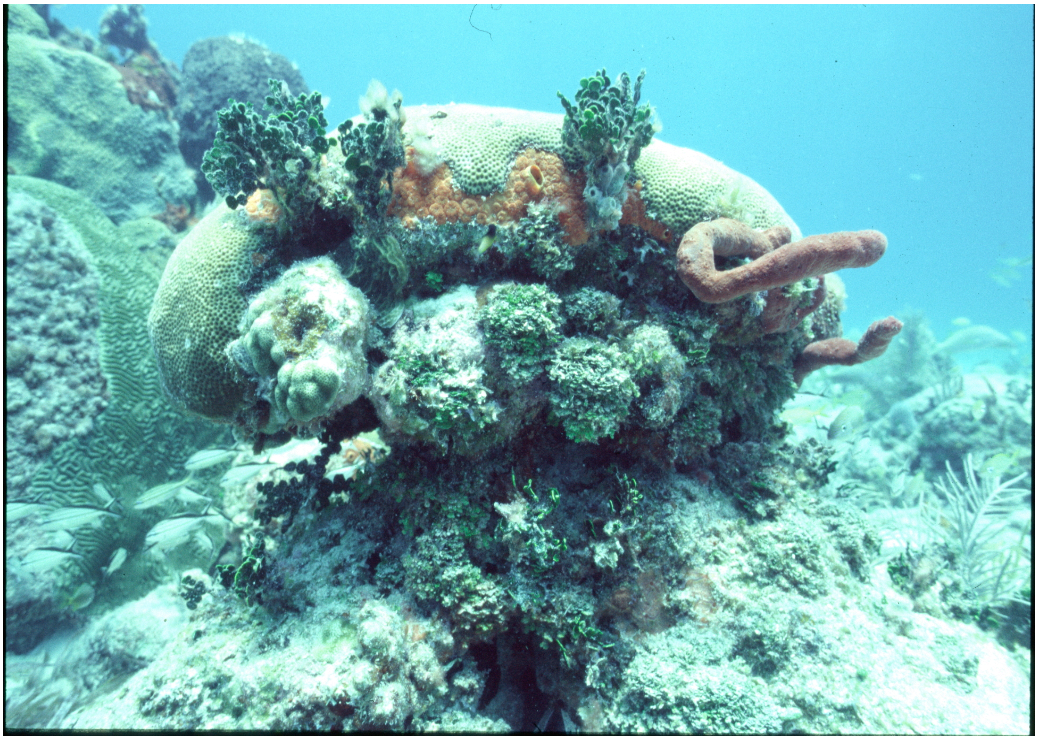


Photos

The process of collecting *Diadema* urchins from the shallow rubble zones.

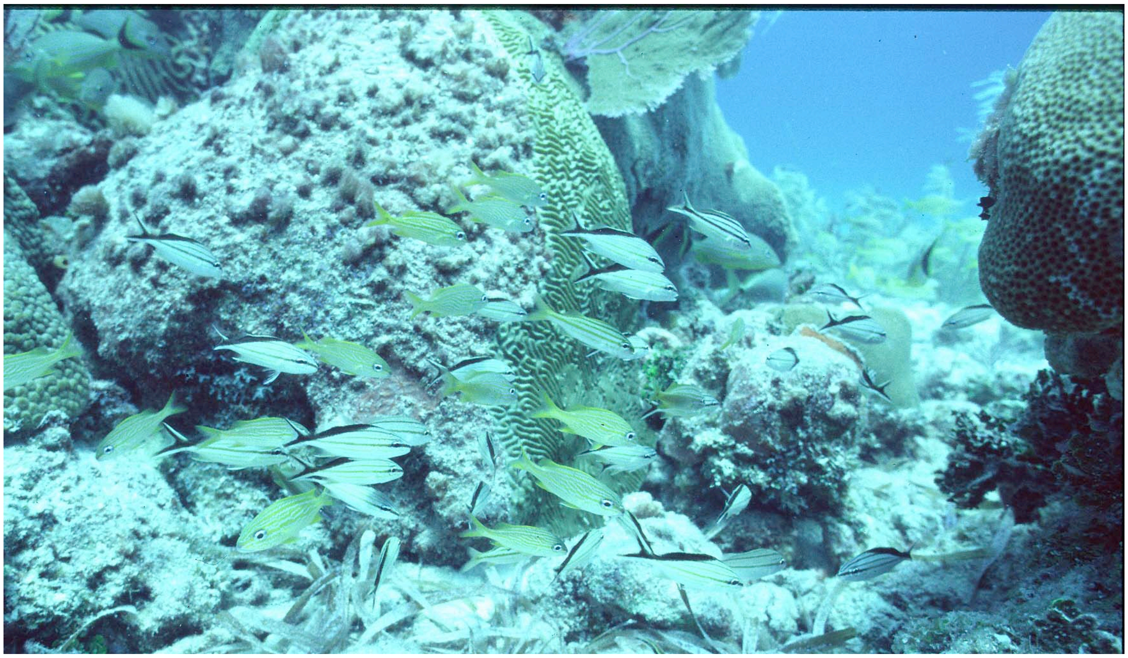


Long view of Experimental Reef # 1



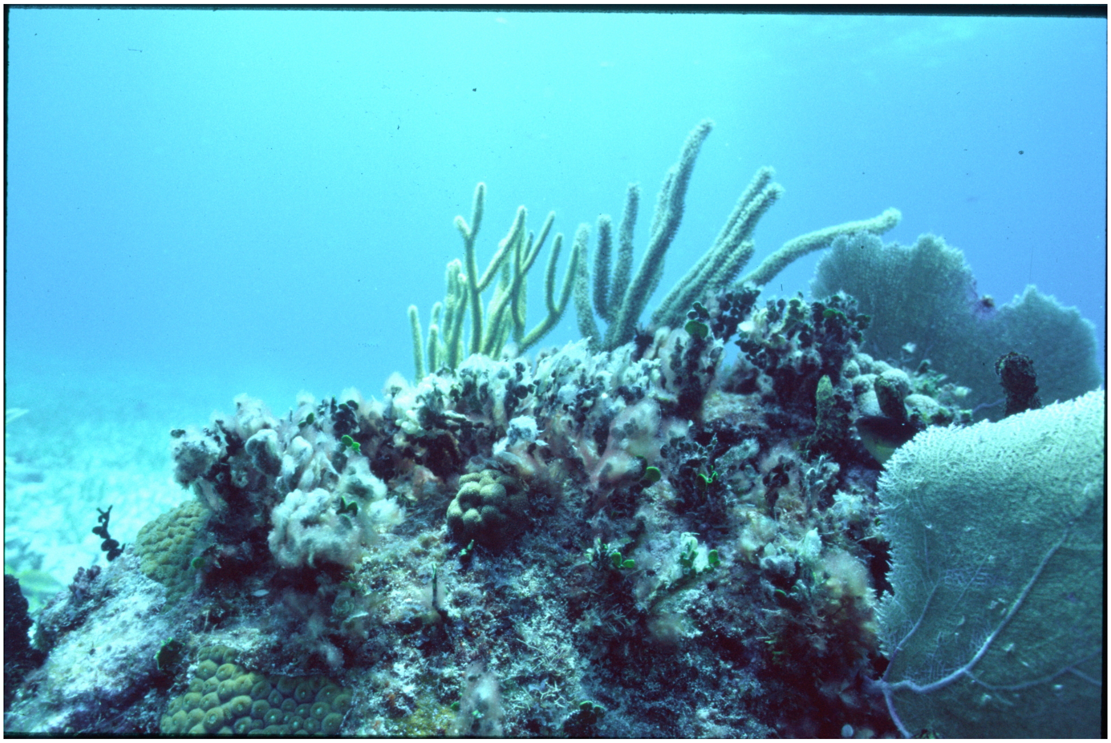
Coral head on Reef # 1 in September 2001 before translocation of Diadema urchins. Note the heavy algal growths.

Same coral head as above in August 2002. Note great reduction in algal growth.

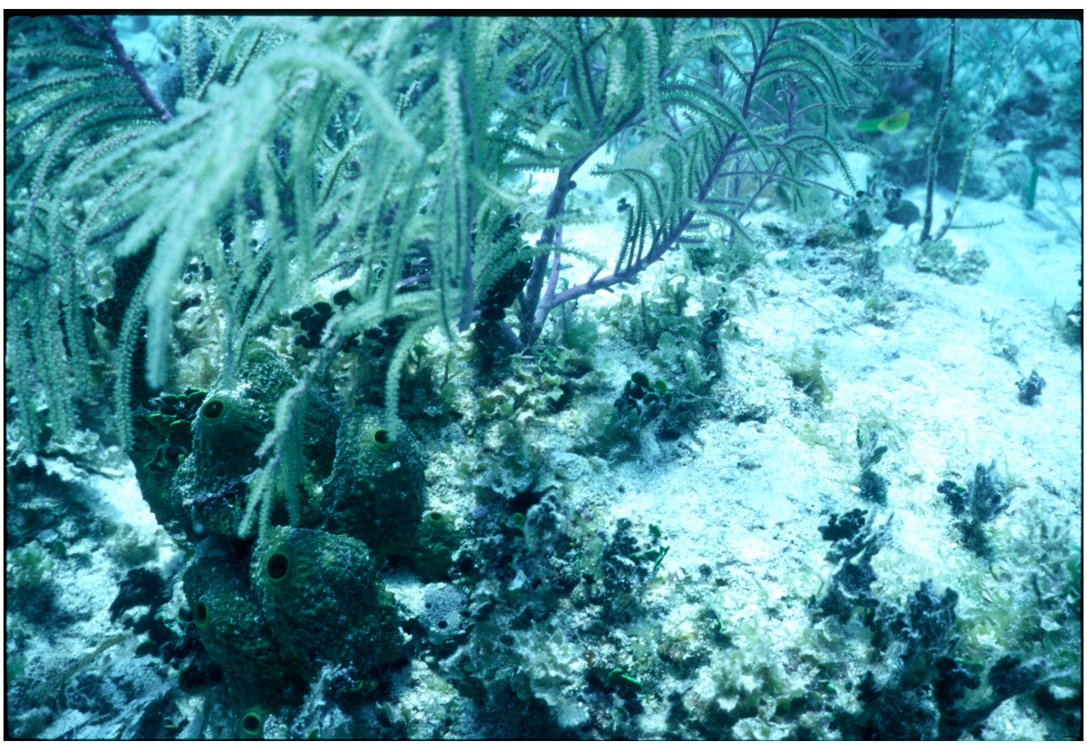


Dying coral head on Reef # 1 in September 2001. Note extent of erosion of living coral tissue and growth of algae on rock surfaces.

Same coral head as above on August 2002. Note removal of algae on rock surfaces and regeneration of coral tissue on upper section of formation.



Typical algal fouling on rock on Reef # 1 before translocation of urchins.



Typical rock reef area on Reef # 1 in August 2002 one year after urchin translocation.